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APPLICATION OF THE SIRS CONCEPT TO NAVY HELICOPTERS.(U)
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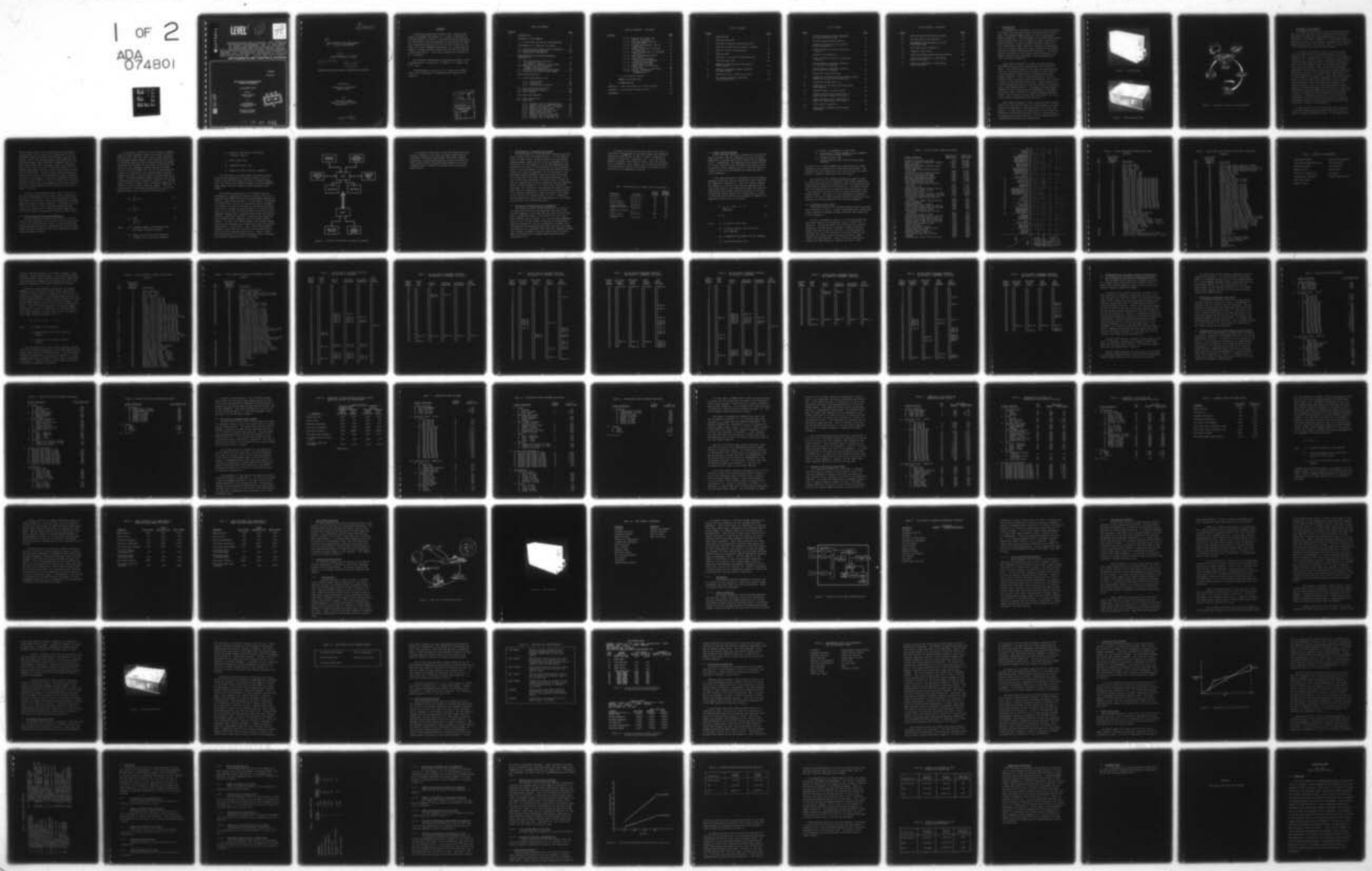

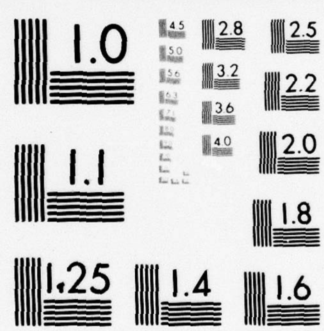

MICROCOPY RESOLUTION TEST CHART

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TECHNOLOGY INCORPORATED

INSTRUMENTS AND CONTROLS DIVISION

0798-05-02

1 October 1979

APPLICATION OF THE SIRS CONCEPT TO NAVY HELICOPTERS

Contract N00019-77-C-0318

Prepared by

Technology Incorporated
Dayton, Ohio

For

Structures Branch
Naval Air Systems Command
Washington, D.C.

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FOREWORD

Technology Incorporated, Dayton, Ohio, prepared this report to document the results of a study it performed on the applicability of SIRS as a fatigue-monitoring technique for the fatigue-critical components of the RH-53D helicopter. This program was sponsored by the Structures Branch of the Naval Air Systems Command, Washington, D.C., under Contract N00019-77-C-0318, entitled "Application of the SIRS Concept to Navy Helicopters." The project monitor for the Navy was Mr. J. McGuinn.

The principal Technology Incorporated personnel on this program were R. B. Johnson, M. S. Moran, J. F. Schott, and M. C. Tyler.

Acknowledgment is given to Mr. R. Malatino of NAVAIR whose early involvement in formulating the study was invaluable.

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1. INTRODUCTION

As demonstrated in Reference 1 for U.S. Army helicopters, the flight condition monitoring (FCM) method can be used to assess the fatigue damage accrued in critical helicopter dynamic components. The development of the FCM System requires first defining given flight conditions (which describe the mission profile) in terms of flight parameter ranges and then establishing flight condition categories (representing one or more flight conditions) which account for the entire spectrum of fatigue-damaging flight operations. By monitoring the time spent in each flight condition category, the damage accrued by each component can be assessed on the basis of actual utilization.

Under Contract DAAJ02-75-C-0050, the FCM system was developed and successfully demonstrated on an AH-1G helicopter. The system defined in the study and developed consists of a microprocessor-based on-board recorder, Figure 1, which monitors various types of damaging helicopter flight conditions. Data are retrieved monthly from the recorder using a portable flight-line retrieval unit, Figure 2, which is also microprocessor based. Retrieved data are stored on miniature data cassettes for further processing on a U.S. Army IBM 360 computer. Accumulated fatigue damage is computed for the various critical components of individual helicopters and is tracked by a highly automated software system. This system is called SIRS, which stands for Structural Integrity Recording System (Figure 3).

This report documents a study, conducted under Contract N00019-77-C-0318 for the Naval Air System Command, to investigate the feasibility of applying SIRS to U.S. Navy helicopters. In this study, the application of the system was defined for the RH-53D helicopter, the cost-effectiveness of the proposed system was analyzed, and the identification of a demonstration program was accomplished.

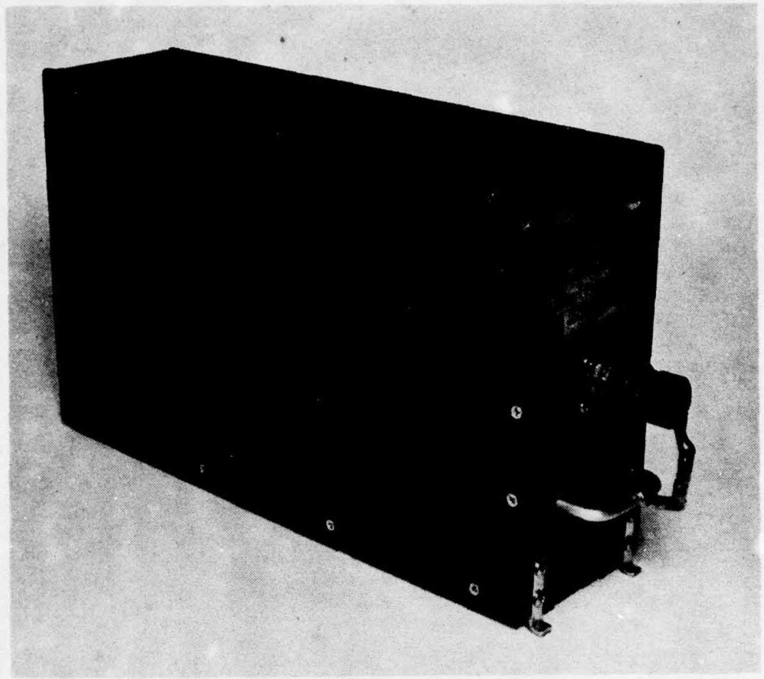

Figure 1. SIRS Recorder

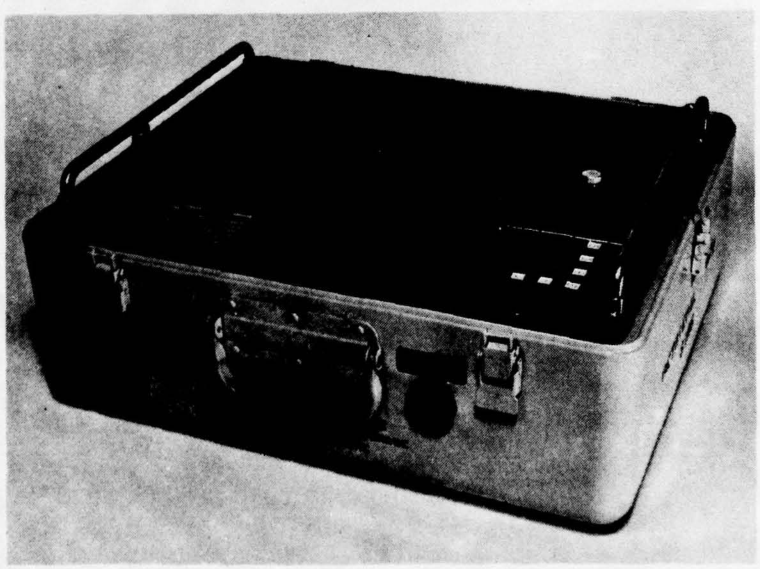

Figure 2. SIRS Retrieval Unit

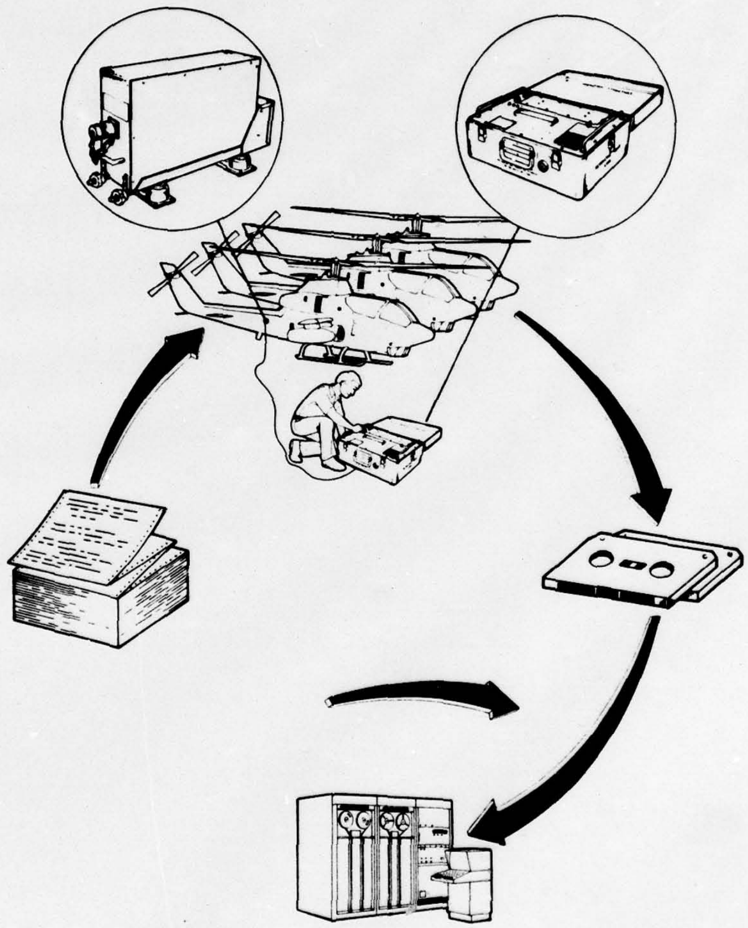

Figure 3. Structural Integrity Recording System

2. STATEMENT OF THE PROBLEM

The current U.S. Navy practice for establishing retirement lives for fatigue-critical components is necessarily conservative because the actual usage experience of each helicopter in the fleet is unknown. If this usage could be monitored so that a cost-effective assessment of the fatigue damage could be made, cost savings could be realized while still maintaining the desired level of safety.

In the past, the specific usage of each helicopter could not realistically be obtained because of cost and weight factors. Consequently, the fatigue-critical dynamic components and airframe would be substantiated based upon an estimated usage spectrum, and the calculated replacement times for each component would be established and tracked based upon flight hours. From time to time, the usage spectrum of the helicopter class would be updated based upon operational reports or by surveying the usage profile of several helicopters in the fleet. These data would be used to resubstantiate the dynamic components of the helicopter. However, the new updated spectrum often would be overestimated under the guise of providing conservatism to the fatigue analysis. Also, the variation between missions would be disregarded because of the inability to define the differences in fatigue damage due to mission variations and to track the effects of these differences on individual components. Consequently, the majority of any fleet of helicopters would be penalized with respect to component replacement because of the conservatively projected usage spectrum of a minority of helicopters.

Better definition of the operational usage spectrum, on the other hand, would allow the prediction of more realistic component replacement times. If the usage of the

the helicopter fleet could be monitored on a helicopter-by-helicopter basis to assess the accumulation of the incremental damage sustained by the helicopter and its components, and if this assessed damage were summed with past and future damage, then individual components could be removed from service when the damage reached some predetermined limit. Such a system of assessment would be a tremendous improvement over the current system based on accumulated flight hours. Since it would provide resolution of the type of exposure to fatigue-damaging flight conditions to which each helicopter is subjected, components being subjected to severe conditions could be removed prior to their premature failure, and those components which are exposed to very mild or non-damaging flight conditions could be continued in service.

The SIRS system developed under contract to the U.S. Army has demonstrated that the correct type of data may be collected on helicopters in the field environment and that these data can be used to track the accumulation of fatigue damage on critical dynamic components. The purpose of this study is to define a flight condition monitoring (FCM) system for a particular U.S. Navy helicopter model and to test it for technical acceptability and cost-effectiveness.

2.1 Flight Condition Monitoring Methodology

The development of the FCM system requires first defining flight conditions which describe the mission profile in terms of flight parameter ranges and then establishing flight condition categories representing one or more flight conditions which account for the entire spectrum of fatigue-damaging flight operations.

In particular, defined in terms of specific combinations of flight parameter ranges, each flight condition category (FCC) represents one or more flight conditions. The component damage caused by each flight condition can be determined when the loads occurring during the flight condition, the frequency of occurrence of the flight condition, and the component fatigue strength are known. To ensure that the damage rate for each flight condition category is conservative, the maximum flight condition damage rate within the given flight condition category is chosen. Then the component damage accrued during a given recording period can be computed by Equation (1), and the flight condition category (FCC) incremental damage can be summed to yield the total component damage. The total recorded time is calculated by Equation (2), and the component fatigue life is calculated by Equation (3).

$$D_k = \sum_{k=1}^{m} C_k \, T_k \tag{1}$$

$$T_t = \sum_{k=1}^{m} T_k \tag{2}$$

$$FL = \frac{T_t}{\sum_{k=1}^{m} D_k} \tag{3}$$

where D_k = component damage accrued during the kth flight condition category

C_k = damage rate in kth flight condition category for a particular component

T_k = amount of time spent in kth flight condition category

T_t = total flight time

FL = component fatigue life

m = number of flight condition categories

The FCM method of fatigue damage assessment requires analyzing the manufacturer's fatigue analysis, first to define a feasible FCM system and then to establish damage rates for each flight condition category for each component. These damage rates are computed using a program called FCMMOD.

The technical feasibility of the defined system is determined by simulating the defined system by the use of a program called SIMULE and testing its performance against an arbitrary operational spectrum. For this study, the spectrum was derived from a variety of data sources and is intended to represent the typical operation of the RH-53D helicopter. The system is defined as being feasible if it predicts lives equal to or less than those predicted by using the original component strength data, component flight loads data and the arbitrary operational spectrum. These lives are called the "upper bound" and are computed using the FATHIP computer program. To verify the FATHIP program, the original fatigue life for each component was calculated by using the original manufacturer's specification. This verification produces component lives which are called the "lower bound" and are used in the cost-effectiveness analysis. Figure 4 shows the relationships of the computer programs used to determine the technical acceptability of a FCM system.

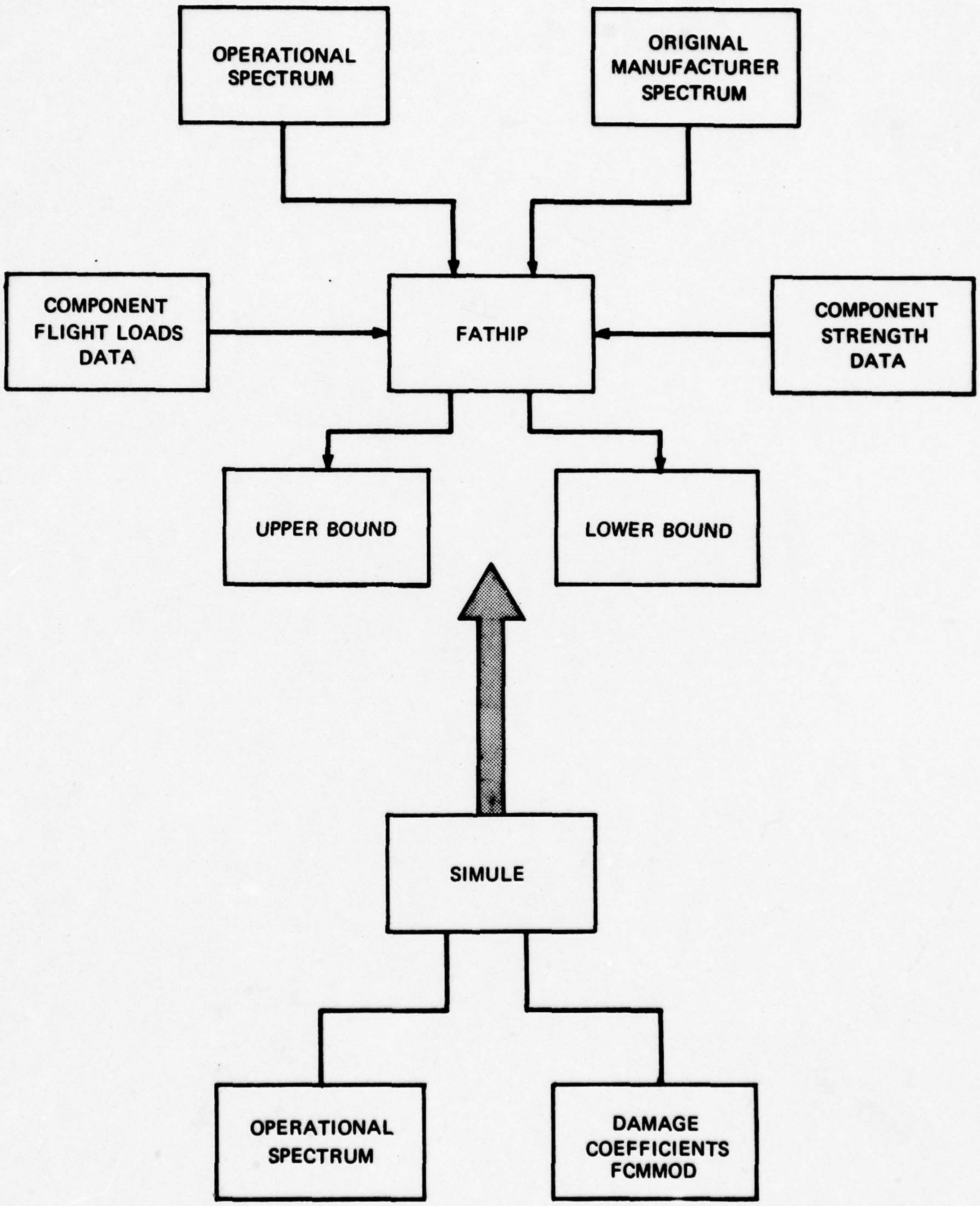

Figure 4. Technical Acceptability Analysis Schematic

It should be noted that a particular FCM system which predicts component lives above the upper bound would be considered technically unacceptable for safety reasons. Conversely, a system which predicts lives at or below the lower bound would be considered unacceptable from a cost viewpoint since it would be no better than the currently used practice.

3. DEVELOPMENT OF A CANDIDATE FCM SYSTEM

The development of a candidate FCM system for any helicopter requires the following procedure: (1) the identification of those flight conditions which have the greatest fatigue-damaging impact on the critical components of the helicopter, (2) the ranking of the fatigue-damaging flight conditions according to both the degree of their damaging effect on the helicopter as a whole and the relative cost to replace the selected components, (3) the selection of the measurable flight parameters whose collective variations will characterize the flight conditions identified in (1), and (4) the final definition of an FCM system in terms of specific combinations of flight parameters and the threshold levels of these parameters. For this study, the RH-53D helicopter was selected as the candidate helicopter on which SIRS would be incorporated. The RH-53D was picked because of its present operational flight restrictions and because of the diversity of missions which it flies. Therefore, the preceding four steps in the development of a FCM system were applied to the RH-53D helicopter.

3.1 Selection of Fatigue-Critical Components

The fatigue-critical RH-53D components to be used in the study were selected by determining those major life-limited components in the main and tail rotor systems which have a significant impact on the RH-53D life-cycle cost. Nine components were selected. For each of these components, Table 1 lists the part number along with the manufacturer-computed fatigue life and the recommended retirement life. The component fatigue damage data along with other pertinent information (e.g., component loads data and component strength data) needed to conduct a fatigue analysis were extracted from the manufacturer's fatigue substantiation reports (References 2-8).

It should be noted that the main rotor blade which is protected by BIM® (Blade Inspection Method) was eliminated during the study because of the U.S. Navy's intention to continue to extend its retirement life. Also, the recommended retirement lives shown in Table 1 were the original lives established; later changes due to flight restrictions or administrative factors which affect this study will be discussed in the appropriate sections.

TABLE 1. SELECTED FATIGUE-CRITICAL COMPONENTS FOR THE RH-53D HELICOPTER

Nomenclature	Part Number	Calculated Fatigue Life (Hrs)	Original Recommended Retirement Life (Hrs)
Blade Fold Pin	65102-11030-101,-102	3450	3400
Control Horn	65102-11041-101	950	1000
Rotating Swashplate	65104-11001-049	980	1000
Stationary Swashplate	65104-11012-041	1760	1800
Tail Rotor Hub Assembly	65358-07046-044	8130	8000
Tail Rotor Pitch Actuating Shaft	65358-07035-041	590	600
Main Rotor Blade Attachment Bolts	SPS 73119	2200	2000
Main Rotor Pushrod	65101-11000-043	18500	7000
Main Rotor Upper Hub Assembly	65103-11010-049	8130	8000

3.2 Flight Condition Ranking

Of the 90 flight conditions identified in the RH-53D design spectrum, some are damaging to the nine selected components in varying degree while others are not damaging at all. Consequently, the damaging flight conditions had to be first identified and then ranked according to both the degree of their damaging effects on the helicopter as a whole and the costs associated with replacing the selected components.

As was done previously in Reference (1), the fatigue-damaging sensitivity rank of each RH-53D flight condition was computed by Equation (4). With the relative expense and complexity of the selected dynamic components being significant factors, this equation provides the means for representing each flight condition relative to its rate of producing fatigue damage to the helicopter as a whole. A normalized rank value was also computed by Equation (5). Equations (4) and (5) are as follows:

$$R = \sum_{\substack{\text{all} \\ \text{components}}} C_F \cdot L_R/L_A \cdot n \cdot D \tag{4}$$

$$\overline{R} = \frac{R}{t} \tag{5}$$

where R = sensitivity rank value

C_F = estimated relative cost factor for eact component

L_R = recommended retirement life for component

L_A = assumed helicopter life

n = number of components per helicopter

D = percentage of fatigue damage to each component due to a given flight condition

$\overline{R}$ = normalized rank value

t = flight condition time from the design usage spectrum

The factor C_F for each component was normalized to 1.0 when compared to the estimated cost of the main rotor blade. The assumed life of the helicopter fleet was 7200 hours or twenty years at a monthly flying hour rate of 30 hours.

The results of the ranking procedure are shown in Table 2. These data were used to determine which flight conditions would have the largest cost benefit so that the synthesized FCM system would ultimately be cost-effective. It should be noted that this ranking did not include the towing conditions since it was planned to include all of the towing conditions in the defined system. The purpose of the ranking was to identify which of the other flight conditions were also important in the monitoring of fatigue damage on the selected components.

3.3 Definition of FCM System

Using the results of the ranking procedure and the relationships presented in Table 3, several FCM systems were synthesized by the grouping of damaging flight conditions into flight condition categories.

System 1, presented in Table 4, is the most general FCM system and requires the parameters listed in Table 5 to be monitored. During the study, this system was tested and determined to be technically acceptable. However, previous flight test work on the U.S. Air Force H-53 helicopter determined that it was not possible to reliably identify longitudinal and lateral control reversals in hover, level flight, and autorotations. Also, it would be difficult to program the SIRS recorder to identify the entry to and

TABLE 2. RH-53D FLIGHT CONDITION RANKING

Flight Condition	Sensitivity Rank Value	Normalized Rank Value
Symmetrical Pullout 130 KCAS	.4432	40.2903
G.G.A.G. (Greatest Ground-Air-Ground)	1.1227	28.0670
Rough Approach	.1857	18.5681
Recovery from Right Sideward Flight	.0557	18.5648
Normal Approach	.4331	10.8264
Level Flight Longitudinal Reversal 130 KCAS	.1003	5.5747
Recovery from Left Sideward Flight	.0140	4.6510
1000 Ft/Min Descent 150 KCAS	.0137	3.4272
Recovery from Rearward Flight	.0093	3.0913
Hovering Longitudinal Reversal	.1005	2.7916
500 Ft/Min Descent 150 KCAS	.0105	2.6160
1500 Ft/Min Descent 150 KCAS	.0052	2.6031
Level Flight Longitudinal Reversal 70 KCAS	.0074	1.4711
Steep Right Turn	1.1751	1.3825
Forward Level Flight 106% V_H 100% N_R	.4036	1.1531
Symmetrical Pullout 70 KCAS	.0124	1.1263
Hovering Right Turn	.0500	1.1106
Level Flight Lateral Reversal 130 KCAS	.0187	1.0370
Autorotation Lateral Reversal 120 KCAS	.0252	.6305
Autorotation Longitudinal Reversal 70 KCAS	.0233	.4665
Forward Level Flight 100% V_H 100% N_R	.9050	.4310
Rotor Engagement	.0034	.3425
Autorotation Entry 70 KCAS	.0003	.3362
Forward Level Flight 106% V_H 105% N_R	.1068	.3051
Level Flight Lateral Reversal 70 KCAS	.0012	.2354
Autorotation Steady 70 KCAS	.0868	.2169
Autorotation Longitudinal Reversal 120 KCAS	.0075	.1870
Autorotation Pullup 70 KCAS	.0004	.1261
Autorotation Rudder Reversal 120 KCAS	.0047	.1166
Forward Level Flight 90% V_H 100% N_R	.9991	.0861
Forward Level Flight 100% V_H 105% N_R	.1718	.0818
Forward Level Flight 20% V_H 105% N_R	.1223	.0719
Steady Right Sideward Flight	.0140	.0467
Steep Left Turn	.0347	.0409
Entry to Rearward Flight	.0000	.0140
Autorotation Turn Right 120 KCAS	.0008	.0114
Steady Rearward Flight	.0028	.0094
Hovering Lateral Reversal	.0003	.0093
Autorotation Turn Left 120 KCAS	.0003	.0048
Landing	.0002	.0042
Forward Level Flight 90% V_H 105% N_R	.0015	.0001

TABLE 3. PARAMETER RELATIONSHIPS FOR RH-53D FLIGHT CONDITIONS

Flight Conditions \ Monitored Parameters	Indicated Airspeed	Pressure Altitude	Outside Air Temp.	Ldg Gear Touchdown	Main Rotor Speed	Engine Torque	Vertical Acceleration	Pitch Attitude	Roll Attitude	Tow Tension	Tow Angle	Long. Stick Position	Lat. Stick Position	Coll. Stick Position	Rudder Pedal Position	Type of Monitoring: Occurrence	Type of Monitoring: Time
1 Rotor Engagement				o	o											o	
2 Left Taxi Turn				o											o		
3 Right Taxi Turn				o											o		
4 Rotor Shutdown				o	o											o	
5 Hover-IGE, 100% N_R	o	o			o	o											o
6 Hover-IGE, 105% N_R	o	o			o	o											o
7 Hover-OGE, 100% N_R	o	o			o	o											o
8 Hover-OGE, 105% N_R	o	o			o	o											o
9-26 Level Flight from 20% V_H to 106% V_H at 100% or 105% N_R	o	o	o		o	o											o
27 Left Hovering Turn	o					o									o		o
28 Right Hovering Turn	o					o									o		o
29 Longitudinal Reversal	o					o						o				o	
30 Lateral Reversal	o					o							o			o	
31 Rudder Reversal	o					o									o	o	
32 Left Sideward Flt-Entry	o					o			o				o				o
33 Left Sideward Flt-Steady	o					o			o				o				o
34 Left Sideward Flt-Recovery	o					o			o				o				o
35 Right Sideward Flt-Entry	o					o			o				o				o
36 Right sideward Flt-Steady	o					o			o				o				o
37 Right Sidward Flt-Recovery	o					o			o				o				o
38 Rearward Flt-Entry	o					o		o				o					o
39 Rearward Flt-Steady	o					o		o				o					o
40 Rearward Flt-Recovery	o					o		o				o					o
41 Takeoff				o												o	
42 Military Power Climb	o	o				o											o
43 Full Power Climb	o	o				o											o
44 Normal Approach	o	o				o	o										o
45 Rough Approach	o	o				o	o										o
46 Landing				o												o	
47 Level Flt Lat. Reversal-70 KCAS	o	o			o	o							o				
48 Level Flt Long. Reversal-70 KCAS	o	o			o	o						o					
49 Level Flt Rudder Reversal-70 KCAS	o	o			o	o									o		
50 Level Flt Lat. Reversal-130 KCAS	o	o			o	o							o				
51 Level Flt Long. Reversal-130 KCAS	o	o			o	o						o					
52 Level Flt Rudder Reversal-130 KCAS	o	o			o	o									o		
53 Left Turn-Moderate	o	o				o	o		o								
54 Right Turn-Moderate	o	o				o	o		o								
55 Left Turn-Steep	o	o				o	o		o								
56 Right Turn-Steep	o	o				o	o		o								
57 Symm. Pullout-70 KCAS	o	o				o	o	o								o	
58 Symm. Pullout-130 KCAS	o	o				o	o	o								o	
59 Dives to 140 KCAS	o	o				o	o	o									o
60-68 Descent at either 500, 1000, or 1500 Ft/Min at 70, 130, and 150 KCAS	o	o				o											o
69 Autorotation Entry-70 KCAS	o	o				o										o	
70 Autorotation Entry-120 KCAS	o	o				o										o	
71 Autorotation Steady-70 KCAS	o	o				o											o
72 Autorotation Steady-120 KCAS	o	o				o											o
73 Autorotation Recovery-150 KCAS	o	o				o										o	
74 Autorotation Recovery-150 KCAS	o	o				o										o	
75 Left Auto Turn-70 KCAS	o	o				o			o								o
76 Left Auto Turn-120 KCAS	o	o				o			o								o
77 Right Auto Turn-70 KCAS	o	o				o			o								o
78 Right Auto Turn-120 KCAS	o	o				o			o								o
79 Long. Auto Reversal-70 KCAS	o	o				o						o				o	
80 Long. Auto Reversal-120 KCAS	o	o				o						o				o	
81 Lat. Auto Reversal-70 KCAS	o	o				o							o			o	
82 Lat. Auto Reversal-120 KCAS	o	o				o							o			o	
83 Rudder Auto Reversal-70 KCAS	o	o				o									o	o	
84 Rudder Auto Reversal-120 KCAS	o	o				o									o	o	
85 Auto Pullup-70 KCAS	o	o				o	o	o								o	
86 Auto Pullup-120 KCAS	o	o				o	o	o								o	
87 Right Towing	o					o				o	o						o
88 Left Towing	o					o				o	o						o
89 Forward Towing	o					o				o	o						o
90 GGAG				o												o	

TABLE 4. FLIGHT CONDITION CATEGORY DEFINITIONS

System 1

FCC No.	Operational Spectrum Condition Number	Description
1	1	Rotor Engagement
2	2	Taxi Turn - Left
	3	Taxi Turn - Right
3	4	Rotor Shutdown
4	5	Hover 100% N_R - IGE
	7	Hover 100% N_R - OGE
5	6	Hover 105% N_R - IGE
	8	Hover 105% N_R - OGE
6	9	Forward Level Flight 20% V_H 100% N_R
7	10	Forward Level Flight 20% V_H 105% N_R
8	11	Forward Level Flight 40% V_H 100% N_R
9	12	Forward Level Flight 40% V_H 105% N_R
10	13	Forward Level Flight 50% V_H 100% N_R
11	14	Forward Level Flight 50% V_H 105% N_R
12	15	Forward Level Flight 60% V_H 100% N_R
13	16	Forward Level Flight 60% V_H 105% N_R
14	17	Forward Level Flight 70% V_H 100% N_R
15	18	Forward Level Flight 70% V_H 105% N_R
16	19	Forward Level Flight 80% V_H 100% N_R
17	20	Forward Level Flight 80% V_H 105% N_R
18	21	Forward Level Flight 90% V_H 100% N_R
19	22	Forward Level Flight 90% V_H 105% N_R
20	23	Forward Level Flight 100% V_H 100% N_R
21	24	Forward Level Flight 100% V_H 105% N_R
22	25	Forward Level Flight 106% V_H 100% N_R
23	26	Forward Level Flight 106% V_H 105% N_R
24	27	Hovering Left Turn
25	28	Hovering Right Turn
26	29	Hovering Longitudinal Reversal
27	30	Hovering Lateral Reversal
28	31	Hovering Rudder Reversal
29	32	Left Sideward Flight - Entry
	34	Left Sideward/Rearward Flight - Recovery
	35	Right Sideward/Rearward Flight - Entry
	37	Right Sideward/Rearward Flight - Recovery
	38	Rearward Flight - Entry
	40	Rearward Flight - Recovery
30	44	Normal Approach
31	42	Climb at Military Power
32	43	Climb at Full Power
33	47	Level Flight Lateral Reversal 70 KCAS
34	48	Level Flight Longitudinal Reversal 70 KCAS

TABLE 4. FLIGHT CONDITION CATEGORY DEFINITIONS (Concluded)

System 1

FCC No.	Operational Spectrum Condition Number	Description
35	49	Level Flight Rudder Reversal 70 KCAS
36	50	Level Flight Lateral Reversal 130 KCAS
37	51	Level Flight Longitudinal Reversal 130 KCAS
38	52	Level Flight Rudder Reversal 130 KCAS
39	53	Moderate Left Turn
40	54	Moderate Right Turn
41	55	Steep Left Turn
42	56	Steep Right Turn
43	57	Symmetrical Pullout 70 KCAS
44	58	Symmetrical Pullout 130 KCAS
45	59	Dives to 140 KCAS
46	60	500 Ft/Min Descent 70 KCAS
47	61	1000 Ft/Min Descent 70 KCAS
48	62	1500 Ft/Min Descent 70 KCAS
49	63	500 Ft/Min Descent 130 KCAS
50	64	1000 Ft/Min Descent 130 KCAS
51	65	1500 Ft/Min Descent 130 KCAS
52	66	500 Ft/Min Descent 150 KCAS
53	67	1000 Ft/Min Descent 150 KCAS
54	68	1500 Ft/Min Descent 150 KCAS
55	69	Autorotation Entry 70 KCAS
56	70	Autorotation Entry 120 KCAS
57	71	Autorotation Steady 70 KCAS
58	72	Autorotation Steady 120 KCAS
59	73	Autorotation Recovery 70 KCAS
60	74	Autorotation Recovery 120 KCAS
61	75	Autorotation Turn Left 70 KCAS
62	76	Autorotation Turn Left 120 KCAS
63	77	Autorotation Turn Right 70 KCAS
64	78	Autorotation Turn Right 120 KCAS
65	79	Autorotation Longitudinal Reversal 70 KCAS
66	80	Autorotation Longitudinal Reversal 120 KCAS
67	81	Autorotation Lateral Reversal 70 KCAS
68	82	Autorotation Lateral Reversal 120 KCAS
69	83	Autorotation Rudder Reversal 70 KCAS
70	84	Autorotation Rudder Reversal 120 KCAS
71	85	Autorotation Pullup 70 KCAS
72	86	Autorotation Pullup 120 KCAS
73	87	Towing Right
74	88	Towing Left
75	89	Towing Forward
76	90	G.G.A.G.
77	33	Steady Left Sideward Flight
	36	Steady Right Sideward Flight
	39	Steady Rearward Flight
78	41	Takeoff
	46	Landing
79	45	Rough Approach

TABLE 5. CANDIDATE FCM PARAMETERS

Indicated Airspeed	Vertical Acceleration
Indicated Airspeed Direction	Pitch Attitude
Pressure Altitude	Roll Attitude
Radar Altitude	Tow Tension
Outside Air Temperature	Tow Angle
Landing Gear Touchdown	Rudder Pedal Position
Main Rotor Speed	
Engine Torque	

recovery from autorotations in a reliable fashion. Consequently, a second system, System 2, was synthesized considering that these flight conditions could not be identified. The resulting FCC categories are presented in Table 6 and would be identified by the same parameters as System 1.

Once the systems had been synthesized, the program FCMMOD was used to generate fatigue damage constants for each of the flight condition categories of each system. As discussed in paragraph 2.1, the maximum damage rate for any flight condition within a flight condition category was used as the damage rate for the flight condition category. Summaries of the damage rates for each system are presented in Tables 7 and 8. For each component, the fatigue damage assessment is based on a damage rate per unit of time for each flight condition category and the total time spent in that flight condition category; that is,

$$D_i = C_1 T_1 + C_2 T_2 + \dots C_j T_j \tag{6}$$

where D_i = damage for ith component

C_j = damage rate for jth flight condition category

T_j = time spent in jth flight condition category

With the definition of the systems completed, each was tested for technical acceptability, using the FCMMOD-derived damage rates, and for cost-effectiveness. The discussion of technical acceptability is presented in Section 4. A more complete definition of System 2 derived above is presented in Section 5. Finally, the cost-effectiveness of System 2 is derived and examined in Section 6.

TABLE 6. FLIGHT CONDITION CATEGORY DEFINITIONS

System 2

FCC No.	Operational Spectrum Condition Number	Description
1	1	Rotor Engagement
2	2	Taxi Turn - Left
	3	Taxi Turn - Right
3	4	Rotor Shutdown
4	5	Hover - IGE at 100% N_R
	7	Hover - OGE at 100% N_R
5	6	Hover - IGE at 105% N_R
	8	Hover - OGE at 105% N_R
6	9	Forward Level Flight 20% V_H 100% N_R
7	10	Forward Level Flight 20% V_H 105% N_R
8	11	Forward Level Flight 40% V_H 100% N_R
9	12	Forward Level Flight 40% V_H 105% N_R
10	13	Forward Level Flight 50% V_H 100% N_R
11	14	Forward Level Flight 50% V_H 105% N_R
	47	Level Flight Lateral Reversal 70 KCAS
	48	Level Flight Longitudinal Reversal 70 KCAS
12	15	Forward Level Flight 60% V_H 100% N_R
13	16	Forward Level Flight 60% V_H 105% N_R
14	17	Forward Level Flight 70% V_H 100% N_R
15	18	Forward Level Flight 70% V_H 105% N_R
16	19	Forward Level Flight 80% V_H 100% N_R
17	20	Forward Level Flight 80% V_H 105% N_R
18	21	Forward Level Flight 90% V_H 100% N_R
19	22	Forward Level Flight 90% V_H 105% N_R
20	23	Forward Level Flight 100% V_H 100% N_R
	50	Level Flight Lateral Reversal 130 KCAS
	51	Level Flight Longitudinal Reversal 130 KCAS
21	24	Forward Level Flight 100% V_H 105% N_R
22	25	Forward Level Flight 106% V_H 100% N_R
23	26	Forward Level Flight 106% V_H 105% N_R
24	27	Hovering Left Turn
25	28	Hovering Right Turn
26	29	Hovering Longitudinal Reversal
27	30	Hovering Lateral Reversal
28	31	Hovering Rudder Reversal
29	32	Left Sideward Flight - Entry
	33	Left Sideward Flight - Steady
	34	Left Sideward Flight - Recovery
30	35	Right Sideward Flight - Entry
	36	Right Sideward Flight - Steady
	37	Right Sideward Flight - Recovery
31	38	Rearward Flight - Entry
	39	Rearward Flight - Steady
	40	Rearward Flight - Recovery
32	44	Normal Approach to Landing

TABLE 6. FLIGHT CONDITION CATEGORY DEFINITIONS (Concluded)

System 2

FCC No.	Operational Spectrum Condition Number	Description
33	42	Climb at Military Power
34	43	Climb at Full Power
35	49	Level Flight Rudder Reversal 70 KCAS
36	52	Level Flight Rudder Reversal 130 KCAS
37	53	Moderate Left Turn
38	54	Moderate Right Turn
39	55	Steep Left Turn
40	56	Steep Right Turn
41	57	Symmetrical Pullout 70 KCAS
42	58	Symmetrical Pullout 130 KCAS
43	59	Dives to 140 KCAS
44	60	500 Ft/Min Descent 70 KCAS
45	61	1000 Ft/Min Descent 70 KCAS
46	62	1500 Ft/Min Descent 70 KCAS
47	63	500 Ft/Min Descent 130 KCAS
48	64	1000 Ft/Min Descent 130 KCAS
49	65	1500 Ft/Min Descent 130 KCAS
50	66	500 Ft/Min Descent 150 KCAS
51	67	1000 Ft/Min Descent 150 KCAS
52	68	1500 Ft/Min Descent 150 KCAS
53	69	Autorotation Entry 70 KCAS
	71	Autorotation Steady 70 KCAS
	73	Autorotation Recovery 70 KCAS
	79	Autorotation Longitudinal Reversal 70 KCAS
	81	Autorotation Lateral Reversal 70 KCAS
54	70	Autorotation Entry 120 KCAS
	72	Autorotation Steady 120 KCAS
	74	Autorotation Recovery 120 KCAS
	80	Autorotation Longitudinal Reversal 120 KCAS
	82	Autorotation Lateral Reversal 120 KCAS
55	75	Autorotation Turn Left 70 KCAS
56	76	Autorotation Turn Left 120 KCAS
57	77	Autorotation Turn Right 70 KCAS
58	78	Autorotation Turn Right 120 KCAS
59	83	Autorotation Rudder Reversal 70 KCAS
60	84	Autorotation Rudder Reversal 120 KCAS
61	85	Autorotation Pullup 70 KCAS
62	86	Autorotation Pullup 120 KCAS
63	87	Towing Right
64	88	Towing Left
65	89	Towing Forward
66	90	GGAG
67	41	Takeoff
68	46	Landing
69	45	Rough Approach

TABLE 7. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 1 BY COMPONENT

Damage Class Number	Blade Fold Pin	Control Horn	Rotating Swashplate	Stationary Swashplate	Tail Rotor Hub Assy
1	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0
18	0.0	0.2852E-02	0.5560E-03	0.0	0.0
19	0.0	0.3330E-03	0.0	0.0	0.0
20	0.0	0.9648E-02	0.1234E-01	0.1667E-01	0.0
21	0.0	0.2320E-02	0.9760E-03	0.0	0.0
22	0.0	0.1741E-01	0.3833E-01	0.5121E-01	0.0
23	0.0	0.9010E-02	0.1065E-01	0.3683E-02	0.0
24	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.5120E-01
26	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0
29	0.3670E 00	0.0	0.0	0.0	0.0
30	0.1626E 00	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0	0.0
36	0.0	0.2222E-01	0.2222E-01	0.7780E-03	0.0
37	0.5556E-02	0.8317E-01	0.1723E 00	0.1111E-01	0.0
38	0.0	0.0	0.0	0.0	0.0
39	0.0	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0
41	0.0	0.2211E-02	0.1986E-01	0.0	0.0
42	0.0	0.2550E-01	0.2780E-02	0.0	0.0
43	0.0	0.1818E-01	0.1818E-01	0.2730E-03	0.0
44	0.2453E 00	0.4001E 00	0.1738E-01	0.1091E 00	0.0
45	0.0	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0	0.0

TABLE 7. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 1 BY COMPONENT (Continued)

Damage Class Number	Blade Fold Pin	Control Horn	Rotating Swashplate	Stationary Swashplate	Tail Rotor Hub Assy
48	0.0	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.0	0.0
51	0.0	0.0	0.0	0.0	0.0
52	0.0	0.2050E-01	0.5000E-02	0.0	0.0
53	0.0	0.5250E-02	0.0	0.0	0.0
54	0.0	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.0	0.0
56	0.0	0.0	0.0	0.0	0.0
57	0.0	0.0	0.0	0.0	0.0
58	0.0	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0
61	0.0	0.0	0.0	0.0	0.0
62	0.0	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0	0.0
64	0.0	0.0	0.0	0.0	0.0
65	0.0	0.0	0.0	0.0	0.0
66	0.0	0.0	0.0	0.0	0.0
67	0.0	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.0	0.0
69	0.0	0.0	0.0	0.0	0.0
70	0.0	0.0	0.0	0.0	0.0
71	0.0	0.0	0.0	0.0	0.0
72	0.0	0.0	0.0	0.0	0.0
73	0.0	0.0	0.0	0.0	0.0
74	0.0	0.0	0.0	0.0	0.0
75	0.0	0.0	0.0	0.0	0.0
76	0.1087E 00	0.1204E 00	0.5882E 00	0.3030E-01	0.2500E 00
77	0.0	0.0	0.0	0.0	0.0
78	0.0	0.0	0.0	0.0	0.0
79	0.1416E-01	0.0	0.0	0.0	0.0

TABLE 7. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 1 BY COMPONENT (Continued)

Damage Class Number	T/R Pitch Actuator Shaft	M/R Blade Attach Bolt	Main Rotor Pushrod	M/R Upper Hub Assy
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.1712E-02
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.4760E-03	0.0	0.0	0.0
21	0.5000E-03	0.0	0.0	0.0
22	0.1976E 00	0.0	0.6543E-03	0.0
23	0.2071E 00	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.3571E 00	0.0	0.0	0.1578E-02
26	0.0	0.0	0.0	0.6642E-01
27	0.0	0.0	0.0	0.2222E-03
28	0.0	0.0	0.0	0.0
29	0.0	0.3333E 00	0.0	0.6467E-01
30	0.0	0.4167E-01	0.0	0.5000E-03
31	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.5600E-02
34	0.0	0.0	0.0	0.3500E-01
35	0.0	0.0	0.0	0.0
36	0.0	0.0	0.0	0.5778E-02
37	0.0	0.0	0.1011E-01	0.1922E-01
38	0.0	0.0	0.0	0.0
39	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0
41	0.0	0.0	0.0	0.0
42	0.0	0.0	0.3411E-02	0.0
43	0.0	0.0	0.0	0.2618E-01

TABLE 7. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 1 BY COMPONENT (Concluded)

Damage Class Number	T/R Pitch Actuator Shaft	M/R Blade Attach Bolt	Main Rotor Pushrod	M/R Upper Hub Assy
44	0.4545E-01	0.4999E 00	0.8173E-01	0.2936E-01
45	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0
48	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.0
51	0.0	0.0	0.0	0.0
52	0.0	0.0	0.0	0.0
53	0.0	0.0	0.0	0.0
54	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.8000E-02
56	0.0	0.0	0.0	0.0
57	0.0	0.0	0.0	0.5160E-02
58	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0
61	0.0	0.0	0.0	0.0
62	0.0	0.0	0.0	0.1143E-03
63	0.0	0.0	0.0	0.0
64	0.0	0.0	0.0	0.2714E-03
65	0.0	0.0	0.0	0.1110E-01
66	0.0	0.0	0.0	0.4450E-02
67	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.1500E-01
69	0.0	0.0	0.0	0.0
70	0.0	0.0	0.0	0.2775E-02
71	0.0	0.0	0.0	0.3000E-02
72	0.0	0.0	0.0	0.0
73	0.0	0.0	0.0	0.0
74	0.0	0.0	0.0	0.0
75	0.0	0.0	0.0	0.0
76	0.2083E 00	0.3623E 00	0.3030E-01	0.4167E-01
77	0.0	0.0	0.0	0.1110E-02
78	0.0	0.0	0.0	0.1000E-03
79	0.0	0.2260E-01	0.0	0.2000E-03

TABLE 8. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 2 BY COMPONENT

Damage Class Number	Blade Fold Pin	Control Horn	Rotating Swashplate	Stationary Swashplate	Tail Rotor Hub Assy
1	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0
18	0.0	0.2852E-02	0.5560E-03	0.0	0.0
19	0.0	0.3325E-03	0.0	0.0	0.0
20	0.5556E-02	0.8317E-01	0.1723E 00	0.1667E-01	0.0
21	0.0	0.2319E-02	0.9762E-03	0.0	0.0
22	0.0	0.1741E-01	0.3833E-01	0.5121E-01	0.0
23	0.0	0.9011E-02	0.1065E-01	0.3683E-02	0.0
24	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.5120E-01
26	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0
30	0.3670E 00	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0
32	0.1626E 00	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0	0.0
36	0.0	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.0	0.0
39	0.0	0.2211E-02	0.1986E-02	0.0	0.0
40	0.0	0.2550E-01	0.2780E-02	0.0	0.0
41	0.0	0.1818E-01	0.1818E-01	0.2727E-03	0.0
42	0.2453E 00	0.4001E 00	0.1738E-01	0.1091E 00	0.0
43	0.0	0.0	0.0	0.0	0.0
44	0.0	0.0	0.0	0.0	0.0
45	0.0	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0	0.0

TABLE 8. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 2 BY COMPONENT (Continued)

Damage Class Number	Blade Fold Pin	Control Horn	Rotating Swashplate	Stationary Swashplate	Tail Rotor Hub Assy
48	0.0	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0	0.0
50	0.0	0.2050E-01	0.5000E-02	0.0	0.0
51	0.0	0.5250E-02	0.0	0.0	0.0
52	0.0	0.0	0.0	0.0	0.0
53	0.0	0.0	0.0	0.0	0.0
54	0.0	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.0	0.0
56	0.0	0.0	0.0	0.0	0.0
57	0.0	0.0	0.0	0.0	0.0
58	0.0	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0
61	0.0	0.0	0.0	0.0	0.0
62	0.0	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0	0.0
64	0.0	0.0	0.0	0.0	0.0
65	0.0	0.0	0.0	0.0	0.0
66	0.1087E 00	0.1204E 00	0.5882E 00	0.3030E-01	0.2500E 00
67	0.0	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.0	0.0
69	0.1416E-01	0.0	0.0	0.0	0.0

TABLE 8. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 2 BY COMPONENT (Continued)

Damage Class Number	T/R Pitch Actuator Shaft	M/R Blade Attach Bolt	Main Rotor Pushrod	M/R Upper Hub Assy
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.1712E-02
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.3500E-01
12	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.4762E-03	0.0	0.1011E-01	0.1922E-01
21	0.5000E-03	0.0	0.0	0.0
22	0.1976E 00	0.0	0.6543E-03	0.0
23	0.2071E 00	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.3571E 00	0.0	0.0	0.1578E-02
26	0.0	0.0	0.0	0.6642E-01
27	0.0	0.0	0.0	0.2222E-03
28	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.2000E-02
30	0.0	0.3333E 00	0.0	0.6467E-01
31	0.0	0.0	0.0	0.2900E-01
32	0.0	0.4167E-01	0.0	0.5000E-03
33	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0
36	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.0
39	0.0	0.0	0.0	0.0
40	0.0	0.0	0.3411E-02	0.0
41	0.0	0.0	0.0	0.2618E-01
42	0.4545E-01	0.4999E 00	0.8173E-01	0.2936E-01
43	0.0	0.0	0.0	0.0

TABLE 8. FATIGUE DAMAGE ASSESSMENT CONSTANTS FOR SYSTEM 2 BY COMPONENT (Concluded)

Damage Class Number	T/R Pitch Actuator Shaft	M/R Blade Attach Bolt	Main Rotor Pushrod	M/R Upper Hub Assy
44	0.0	0.0	0.0	0.0
45	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0
48	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.0
51	0.0	0.0	0.0	0.0
52	0.0	0.0	0.0	0.0
53	0.0	0.0	0.0	0.1110E-01
54	0.0	0.0	0.0	0.1500E-01
55	0.0	0.0	0.0	0.0
56	0.0	0.0	0.0	0.1143E-03
57	0.0	0.0	0.0	0.0
58	0.0	0.0	0.0	0.2714E-03
59	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.2775E-02
61	0.0	0.0	0.0	0.3000E-02
62	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0
64	0.0	0.0	0.0	0.0
65	0.0	0.0	0.0	0.0
66	0.2083E 00	0.3623E 00	0.3030E-01	0.4167E-01
67	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.1000E-03
69	0.0	0.2260E-01	0.0	0.2000E-03

4. DETERMINATION OF FCM SYSTEM TECHNICAL ACCEPTABILITY

4.1 Basic Definition of Technical Acceptance Criteria

The assessment of the technical acceptability of the two candidate FCM systems described in Tables 4 and 6 requires analyzing the proposed system with the aid of two computer programs, FATHIP and SIMULE.

According to the criteria discussed in Section 2, an FCM system must be capable of predicting, for each component, fatigue lives that fall between the conservative lower bound, which is based upon the design usage spectrum, and a realistic upper bound, which is based upon an arbitrary operational usage spectrum. Ideally, the FCM system should be able to identify each and every flight condition within the operational spectrum with perfect fidelity in order to be most cost-effective. However, as discussed in Section 3, certain flight conditions could not practically be monitored. Consequently, inherent conservation built into the FCM system definition will cause the predicted lives of the selected components to be below the upper bound. Also, although it is technically acceptable for the FCM system to predict component lives below the lower bound, the system would not be deemed acceptable in this case since the resulting system might not be cost-effective.

Program FATHIP computes component fatigue damage on the basis of component strength data, component flight loads data and the design usage spectrum. This analysis program duplicates the manufacturer's analysis.

Program SIMULE simulates the operation of a FCM system by computing component fatigue lives from the FCM-generated fatigue damage coefficients in a given usage spectrum.

The application of the technical acceptance criteria requires the following: (1) the definition of the lower bounds for component fatigue lives, (2) the substantiation of a fatigue damage assessment model, specifically the computer program FATHIP, (3) the derivation of realistic upper bounds for the component fatigue lives in an operational usage spectrum, and (4) the testing of the FCM system using the SIMULE program.

4.2 Definition of Component Lower Bounds

As indicated in Section 3, Table 1 includes the manufacturer-computed fatigue lives and the recommended retirement lives for the nine selected components. The manufacturer's computations were based upon the design utilization spectrum summarized in Table 9. Since such a spectrum is conventionally more severe than the actual utilization anticipated during the life of the helicopter, the computed fatigue lives are conservative. To conform with the methodology outlined in Section 2, the calculated fatigue lives were defined as the lower bounds for evaluation of the system's technical acceptability.

4.3 Substantiation of the Fatigue Damage Assessment Model

FATHIP, the fatigue damage assessment model, calculates incremental component fatigue damage similarly as the RH-53D manufacturer's process. In order to use this program in the study, it was necessary to substantiate its computational process so that variations in the usage spectrum could be investigated. To substantiate this model, the same component S/N data, component flight loads data, and design usage spectrum used in the manufacturer's analysis process were used as input data for FATHIP. If FATHIP yields fatigue lives agreeing closely with those derived by the manufacturer, the model is substantiated.

TABLE 9. DESIGN UTILIZATION SPECTRUM

Flight Conditions	% of Flight Time
I. Ground Conditions	
A. Rotor Engagement	.010
B. Left Taxi Turn	.400
C. Right Taxi Turn	.400
D. Rotor Shutdown	.010
II. Power-On Flight - Cruise	
A. Hover	
1. IGE 100% N_R	2.100
2. IGE 105% N_R	2.100
3. OGE 100% N_R	2.100
4. OGE 105% N_R	2.100
B. Forward Level Flight	
1. 20% V_H 100% N_R	1.700
2. 20% V_H 105% N_R	1.700
3. 40% V_H 100% N_R	.700
4. 40% V_H 105% N_R	.700
5. 50% V_H 100% N_R	.700
6. 50% V_H 105% N_R	.700
7. 60% V_H 100% N_R	1.700
8. 60% V_H 105% N_R	1.700
9. 70% V_H 100% N_R	2.900
10. 70% V_H 105% N_R	2.900
11. 80% V_H 100% N_R	3.800
12. 80% V_H 105% N_R	3.800
13. 90% V_H 100% N_R	11.600
14. 90% V_H 105% N_R	11.600
15. 100% V_H 100% N_R	2.100
16. 100% V_H 105% N_R	2.100
17. 106% V_H 100% N_R	.350
18. 106% V_H 105% N_R	.350
III. Power-On Flight - Maneuvers	
A. Hover	
1. Left Turn	.045
2. Right Turn	.045
3. Longitudinal Reversal	.036
4. Lateral Reversal	.027
5. Rudder Reversal	.027
B. Sideward Flight	
1. Entry Left	.003
2. Steady Left	.300
3. Recovery Left	.003
4. Entry Right	.003
5. Steady Right	.300
6. Recovery Right	.003
C. Rearward Flight	
1. Entry	.003
2. Steady	.300
3. Recovery	.003

TABLE 9. DESIGN UTILIZATION SPECTRUM (Continued)

Flight Conditions	% of Flight Time
D. Climb	
1. Takeoff	.040
2. Military Power	.700
3. Full Power	2.100
E. Approach and Landing	
1. Normal Approach	.040
2. Rough Approach	.010
3. Landing	.040
F. Level Flight Reversals	
1. Lateral 70 KCAS	.005
2. Longitudinal 70 KCAS	.005
3. Rudder 70 KCAS	.005
4. Lateral 130 KCAS	.018
5. Longitudinal 130 KCAS	.018
6. Rudder 130 KCAS	.018
G. Turns	
1. Left - Moderate	.850
2. Right - Moderate	.850
3. Left - Steep	.850
4. Right - Steep	.850
H. Descent	
1. Symmetrical Pullout 70 KCAS	.011
2. Symmetrical Pullout 130 KCAS	.011
3. Dives to 140 KCAS	.250
IV. Partial Power Maneuvers	
A. Descent 500 Ft/Min 70 KCAS	.005
B. Descent 1000 Ft/Min 70 KCAS	.005
C. Descent 1500 Ft/Min 70 KCAS	.005
D. Descent 500 Ft/Min 130 KCAS	.008
E. Descent 1000 Ft/Min 130 KCAS	.007
F. Descent 1500 Ft/Min 130 KCAS	.007
G. Descent 500 Ft/Min 150 KCAS	.004
H. Descent 1000 Ft/Min 150 KCAS	.004
I. Descent 1500 Ft/Min 150 KCAS	.002
V. Autorotation	
A. Forward Flight	
1. Entry 70 KCAS	.001
2. Entry 120 KCAS	.003
3. Steady 70 KCAS	.400
4. Steady 120 KCAS	.400
5. Recovery 70 KCAS	.002
6. Recovery 120 KCAS	.002
B. Turns	
1. Left 70 KCAS	.070
2. Left 120 KCAS	.070
3. Right 70 KCAS	.070
4. Right 120 KCAS	.070

TABLE 9. DESIGN UTILIZATION SPECTRUM (Concluded)

Flight Conditions	% of Flight Time
C. Reversals	
1. Longitudinal 70 KCAS	.050
2. Longitudinal 120 KCAS	.040
3. Lateral 70 KCAS	.050
4. Lateral 120 KCAS	.040
5. Rudder 70 KCAS	.050
6. Rudder 120 KCAS	.040
7. Pullup 70 KCAS	.003
8. Pullup 120 KCAS	.001
VI. Towing	
A. Right	1.500
B. Left	1.500
C. Forward	1.500
VII. G.G.A.G.	.040

For both the manufacturer's and the FATHIP computations, Table 10 lists the fatigue damage accrued by each of the nine selected RH-53D components during 100 hours of operation in the design usage spectrum and the fatigue life of each component. The close correlation of the two sets of data verified FATHIP as a valid fatigue damage assessment model for the RH-53D helicopter.

4.4 Derivation of Component Upper Bounds

The first task in the process of deriving upper bounds for component fatigue lives is the construction of an operational usage spectrum. This operational spectrum must be defined in terms of the same flight conditions that were used to define the design usage spectrum. The operational usage spectrum derived for the RH-53D helicopter is presented in Table 11. This spectrum was synthesized from several data sources, References 9 through 11. For the purposes of this study, it was assumed that the current flight restrictions were not in effect.

No one data source was adequate for the definition of the operational usage spectrum. Data from Reference 9 were used as a primary source; these data were gathered by the Naval Air Development Center on four CH-53A helicopters. Supplementing these data were data gathered by Technology Incorporated on eleven USAF HH-53C helicopters. Finally, data gathered by the manufacturer and NAVAIR personnel resulted in an estimate of the towing spectrum as reported in Reference 11.

The percentage of time spent on the ground was taken from data presented in Reference 4. This time was assigned to the four GROUND conditions in the same ratios as the ground conditions in the design spectrum. The higher percentage of time experienced while operating on the ground has been seen in both U.S. Army and U.S. Air Force helicopter data and is considered to be applicable to U.S. Navy operations also.

TABLE 10. COMPARISON OF MANUFACTURER AND FATHIP FATIGUE DAMAGE AND FATIGUE LIFE COMPUTATIONS

	Design Spectrum			
	Manufacturer's Computations*		FATHIP Results	
Component	Fatigue Damage in 100 Hrs.	Fatigue Life (Hours)	Fatigue Damage in 100 Hrs.	Fatigue Life (Hours)
Blade Fold Pin	.0290	3450	.0289	3459
Control Horn	.1052	950	.1063	941
Rotating Swashplate	.1020	980	.1020	981
Stationary Swashplate	.0568	1760	.0568	1759
Main Rotor Pushrod	.0054	18500	.0054	18445
Tail Rotor Hub Assembly	.0123	8130	.0123	8127
Tail Rotor Pitch Actuator Shaft	.1687	590	.1686	593
Main Rotor Upper Hub Assembly	.0123	8130	.0126	7953

*Reference 2

TABLE 11. OPERATIONAL USAGE SPECTRUM

Flight Conditions	Flight Regime	% of Flight Time
I. Ground Conditions		
A. Rotor Engagement	-	.268
B. Left Taxi Turn	-	10.732
C. Right Taxi Turn	-	10.732
D. Rotor Shutdown	-	.268
II. Power On Flight - Cruise		
A. Hover		
1. IGE 100% N_R	H	.912
2. IGE 105% N_R	H	.912
3. OGE 100% N_R	H	.912
4. OGE 105% N_R	H	.912
B. Forward Level Flight		
1. 20% V_H 100% N_R	L	1.373
2. 20% V_H 105% N_R	L	1.373
3. 40% V_H 100% N_R	L	1.061
4. 40% V_H 105% N_R	L	1.061
5. 50% V_H 100% N_R	L	1.426
6. 50% V_H 105% N_R	L	1.426
7. 60% V_H 100% N_R	L	1.239
8. 60% V_H 105% N_R	L	1.239
9. 70% V_H 100% N_R	L	1.328
10. 70% V_H 105% N_R	L	1.328
11. 80% V_H 100% N_R	L	.000
12. 80% V_H 105% N_R	L	2.692
13. 90% V_H 100% N_R	L	.000
14. 90% V_H 105% N_R	L	2.034
15. 100% V_H 100% N_R	L	.000
16. 100% V_H 105% N_R	L	.232
17. 106% V_H 100% N_R	L	.000
18. 106% V_H 105% N_R	L	.018
III. Power-On Flight - Maneuvers		
A. Hover		
1. Left Turn	H	.020
2. Right Turn	H	.020
3. Longitudinal Reversal	H	.016
4. Lateral Reversal	H	.012
5. Rudder Reversal	H	.012
B. Sideward Flight		
1. Entry Left	L	.001
2. Steady Left	L	.105
3. Recovery Left	L	.001
4. Entry Right	L	.001
5. Steady Right	L	.105
6. Recovery Right	L	.001
C. Rearward Flight		
1. Entry	L	.001
2. Steady	L	.105
3. Recovery	L	.001

TABLE 11. OPERATIONAL USAGE SPECTRUM (Continued)

Flight Conditions	Flight Regime	% of Flight Time
D. Climb		
1. Takeoff	-	.035
2. Military Power	C	2.795
3. Full Power	C	8.386
E. Approach and Landing		
1. Normal Approach	-	.035
2. Rough Approach	-	.009
3. Landing	-	.035
F. Level Flight Reversals		
1. Lateral 70 KCAS	L	.002
2. Longitudinal 70 KCAS	L	.002
3. Rudder 70 KCAS	L	.002
4. Lateral 130 KCAS	L	.006
5. Longitudinal 130 KCAS	L	.006
6. Rudder 130 KCAS	L	.006
G. Turns		
1. Left - Moderate	L	.297
2. Right - Moderate	L	.297
3. Left - Steep	L	.297
4. Right - Steep	L	.297
H. Descent		
1. Symmetrical Pullout 70 KCAS	-	.018
2. Symmetrical Pullout 130 KCAS	-	.018
3. Dives to 140 KCAS	D	.520
IV. Partial Power Maneuvers		
A. Descent 500 Ft/Min 70 KCAS	D	2.086
B. Descent 1000 Ft/Min 70 KCAS	D	2.086
C. Descent 1500 Ft/Min 70 KCAS	D	2.086
D. Descent 500 Ft/Min 130 KCAS	D	1.375
E. Descent 1000 Ft/Min 130 KCAS	D	1.203
F. Descent 1500 Ft/Min 130 KCAS	D	1.203
G. Descent 500 Ft/Min 150 KCAS	D	.151
H. Descent 1000 Ft/Min 150 KCAS	D	.151
I. Descent 1500 Ft/Min 150 KCAS	D	.075
V. Autorotation		
A. Forward Flight		
1. Entry 70 KCAS	-	.001
2. Entry 120 KCAS	-	.003
3. Steady 70 KCAS	-	.400
4. Steady 120 KCAS	-	.400
5. Recovery 70 KCAS	-	.002
6. Recovery 120 KCAS	-	.002
B. Turns		
1. Left 70 KCAS	-	.070
2. Left 120 KCAS	-	.070
3. Right 70 KCAS	-	.070
4. Right 120 KCAS	-	.070

TABLE 11. OPERATIONAL USAGE SPECTRUM (Concluded)

Flight Conditions	Flight Regime	% of Flight Time
C. Reversals		
1. Longitudinal 70 KCAS	-	.050
2. Longitudinal 120 KCAS	-	.040
3. Lateral 70 KCAS	-	.050
4. Lateral 120 KCAS	-	.040
5. Rudder 70 KCAS	-	.050
6. Rudder 120 KCAS	-	.040
7. Pullup 70 KCAS	-	.003
8. Pullup 120 KCAS	-	.001
VI. Towing		
A. Right	-	5.770
B. Left	-	5.770
C. Forward	-	19.460
VII. G.G.A.G.	-	.035

The time spent in FORWARD LEVEL FLIGHT has been adjusted to account for all flight above 125 knots to be conducted at 105% N_R (rotor speed). Since SIRS can be used to track damaging flight conditions, it was assumed that flight operations at speeds up to 106% V_H would be allowed to occur, i.e., the current flight restriction would be waived.

The number of TAKEOFFS and LANDINGS were taken from data presented in Reference 3. It is assumed that there was one G.G.A.G. cycle for each TAKEOFF and LANDING. SYMMETRICAL PULLOUTS were identified as positive normal accelerations greater than or equal to 1.35 g's. Their frequency of occurrence was taken from a cumulative frequency of occurrence curve presented in Reference 3. This frequency was then translated into percentage of flight time using the maneuvers per 100 hours rate used in the design spectrum for this flight condition.

None of the available data sources adequately identified the time spent in the AUTOROTATION mission segment because of small data samples. Since the design spectrum is conventionally more conservative than operational usage, the percentages of flight time spent in AUTOROTATION in the design spectrum were assigned to AUTOROTATION in the operational spectrum. The percentage of flight time spent in TOWING was taken from Reference 5. This too, was assigned the same ratios as the design spectrum.

All of the flight conditions discussed so far are identified by a dash in the Flight Regime column in Table 11. Most of the remaining flight conditions were assigned to one of the four flight regimes: climb, hover, descent, or level flight. These flight regimes are identified by the letters C, H, D, and L, respectively in Table 11. In Reference 3, total flight time is broken down by percentage into the four flight regimes. The percentages of flight

time for all the flight conditions identified by a dash in Table 11 are summed and the sum was subtracted from 100 percent. This result was used as a multiplier to each of the percentages of flight time indicated for each of the four flight regimes. This operation normalized the operational spectrum to approximately 100 percent. The adjusted percentages for each flight regimes were then assigned to their flight conditions in the same ratios as the design spectrum; in certain cases, the ratios were adjusted as a result of the Reference 4 data. This completed the derivation of the operational usage spectrum. Table 12 presents the design and operational spectrum side by side for easier comparison. Each of the 90 flight conditions is numbered for future reference.

Once the operational usage spectrum was synthesized, it was processed in the FATHIP program to determine the fatigue lives for each of the nine components when exposed to this milder spectrum. These fatigue lives were defined as the upper bound for each of the components. Table 13 lists the upper and lower bounds for each of the components. It should be noted that for the blade fold pin and main rotor blade attachment bolt, the upper and lower bounds are nearly identical so that no benefit can be expected to be derived from SIRS for these components. However, for the other components, benefits should be derived from using SIRS.

4.5 Testing of FCM System Using SIMULE

To be considered technically acceptable, a candidate FCM system must be capable of predicting for each of the selected components a fatigue life within the upper and lower bounds for the conditions described by the operational spectrum. To simulate the prediction of component fatigue life, a computer program, SIMULE, was used. The SIMULE program identifies the output of the on-board FCM recorder, assesses the fatigue damage according to the recorder out-

TABLE 12. COMPARISON OF THE DESIGN AND OPERATIONAL USAGE SPECTRA

Flight Condition	Ref. No.	Spectrum Design	Spectrum Operational
I. Ground Conditions			
A. Rotor Engagement	1	.010	.268
B. Left Taxi Turn	2	.400	10.732
C. Right Taxi Turn	3	.400	10.732
D. Rotor Shutdown	4	.010	.268
II. Power-On Flight - Cruise			
A. Hover			
1. IGE 100% N_R	5	2.100	.912
2. IGE 105% N_R	7	2.100	.912
3. OGE 100% N_R	6	2.100	.912
4. OGE 105% N_R	8	2.100	.912
B. Forward Level Flight			
1. 20% V_H 100% N_R	9	1.700	1.373
2. 20% V_H 105% N_R	10	1.700	1.373
3. 40% V_H 100% N_R	11	.700	1.061
4. 40% V_H 105% N_R	12	.700	1.061
5. 50% V_H 100% N_R	13	.700	1.426
6. 50% V_H 105% N_R	14	.700	1.426
7. 60% V_H 100% N_R	15	1.700	1.239
8. 60% V_H 105% N_R	16	1.700	1.239
9. 70% V_H 100% N_R	17	2.900	1.328
10. 70% V_H 105% N_R	18	2.900	1.328
11. 80% V_H 100% N_R	19	3.800	.000
12. 80% V_H 105% N_R	20	3.800	2.692
13. 90% V_H 100% N_R	21	11.600	.000
14. 90% V_H 105% N_R	22	11.600	2.034
15. 100% V_H 100% N_R	23	2.100	.000
16. 100% V_H 105% N_R	24	2.100	.232
17. 106% V_H 100% N_R	25	.350	.000
18. 106% V_H 105% N_R	26	.350	.018
III. Power-On Flight - Maneuvers			
A. Hover			
1. Left Turn	27	.045	.020
2. Right Turn	28	.045	.020
3. Longitudinal Reversal	29	.036	.016
4. Lateral Reversal	30	.027	.012
5. Rudder Reversal	31	.027	.012
B. Sideward Flight			
1. Entry Left	32	.003	.001
2. Steady Left	33	.300	.105
3. Recovery Left	34	.003	.001
4. Entry Right	35	.003	.001
5. Steady Right	36	.300	.105
6. Recovery Right	37	.003	.001

TABLE 12. COMPARISON OF THE DESIGN AND OPERATIONAL USAGE SPECTRA (Continued)

Flight Condition	Ref. No.	Spectrum Design	Spectrum Operational
C. Rearward Flight			
1. Entry	38	.003	.001
2. Steady	39	.300	.105
3. Recovery	40	.003	.001
D. Climb			
1. Takeoff	41	.040	.035
2. Military Power	42	.700	2.795
3. Full Power	43	2.100	8.386
E. Approach and Landing			
1. Normal Approach	44	.040	.035
2. Rough Approach	45	.010	.009
3. Landing	46	.040	.035
F. Level Flight Reversals			
1. Lateral 70 KCAS	47	.005	.002
2. Longitudinal 70 KCAS	48	.005	.002
3. Rudder 70 KCAS	49	.005	.002
4. Lateral 130 KCAS	50	.018	.006
5. Longitudinal 130 KCAS	51	.018	.006
6. Rudder 130 KCAS	52	.018	.006
G. Turn			
1. Left - Moderate	53	.850	.297
2. Right - Moderate	54	.850	.297
3. Left - Steep	55	.850	.297
4. Right - Steep	56	.850	.297
H. Descent			
1. Symmetrical Pullout 70 KCAS	57	.011	.018
2. Symmetrical Pullout 130 KCAS	58	.011	.018
3. Dives to 140 KCAS	59	.250	.520
IV. Partial Power Maneuvers			
A. Descent 500 Ft/Min 70 KCAS	60	.005	2.086
B. Descent 1000 Ft/Min 70 KCAS	61	.005	2.086
C. Descent 1500 Ft/Min 70 KCAS	62	.005	2.086
D. Descent 500 Ft/Min 130 KCAS	63	.008	1.375
E. Descent 1000 Ft/Min 130 KCAS	64	.007	1.203
F. Descent 1500 Ft/Min 130 KCAS	65	.007	1.203
G. Descent 500 Ft/Min 150 KCAS	66	.004	.151
H. Descent 1000 Ft/Min 150 KCAS	67	.004	.151
I. Descent 1500 Ft/Min 150 KCAS	68	.002	.075

TABLE 12. COMPARISON OF THE DESIGN AND OPERATIONAL USAGE SPECTRA (Concluded)

Flight Condition	Ref. No.	Spectrum Design	Spectrum Operational
V. Autorotation			
A. Forward Flight			
1. Entry 70 KCAS	69	.001	.001
2. Entry 120 KCAS	70	.003	.003
3. Steady 70 KCAS	71	.400	.400
4. Steady 120 KCAS	72	.400	.400
5. Recovery 70 KCAS	73	.002	.002
6. Recovery 120 KCAS	74	.002	.002
B. Turns			
1. Left 70 KCAS	75	.070	.070
2. Left 120 KCAS	76	.070	.070
3. Right 70 KCAS	77	.070	.070
4. Right 120 KCAS	78	.070	.070
C. Reversals			
1. Longitudinal 70 KCAS	79	.050	.050
2. Longitudinal 120 KCAS	80	.040	.040
3. Lateral 70 KCAS	81	.050	.050
4. Lateral 120 KCAS	82	.040	.040
5. Rudder 70 KCAS	83	.050	.050
6. Rudder 120 KCAS	84	.040	.040
7. Pullup 70 KCAS	85	.003	.003
8. Pullup 120 KCAS	86	.001	.001
VI. Towing			
A. Right	87	1.500	5.770
B. Left	88	1.500	5.770
C. Forward	89	1.500	19.460
VII. C.G.A.G.	90	.040	.035

TABLE 13. COMPONENT UPPER AND LOWER BOUNDS

Component	Lower Bound (Hrs)	Upper Bound (Hrs)
Blade Fold Pin	3459	3699
Control Horn	941	3863
Rotating Swashplate	981	1787
Stationary Swashplate	1759	31586
Tail Rotor Hub Assembly	8127	10232
Tail Rotor Pitch Actuating Shaft	593	5236
Main Rotor Blade Attachment Bolt	2210	2286
Main Rotor Pushrod	18445	27734
Main Rotor Upper Hub Assembly	7953	10052

put, and computes the fatigue life of the component on the basis of the fatigue damage assessments and the accumulated flight time. The SIMULE program was run for a 100-hour sample of the operational usage spectrum from which the recorder output was simulated. The output of the recorder was simulated by assigning the flight conditions of the operational spectrum to the flight condition categories of the FCM system according to the anticipated helicopter response. The time and/or occurrences of the flight conditions in the 100-hour sample were then accumulated in the flight condition categories (FCC's) of the monitoring system. Damage fractions were computed from the recorded output and the derived FCMMOD constants by using Equation (7) and then summed to determine the damage accumulated by the components in the 100-hour sample.

$$D_i = FCC_j \cdot T_j \tag{7}$$

where D_i = incremental damage for ith component

FCC_j = incremental damage rate for particular flight condition category

T_j = time spent in particular flight condition category

Assuming that the 100-hour sample is an average, the component fatigue life as predicted by the FCM system was computed. Thus the SIMULE program computed the fatigue lives anticipated for the usage identified by the operational spectrum.

Testing of System 1 by SIMULE yielded the results presented in Table 14. As can be seen, all of the FCM predicted lives fall between the upper and lower bounds except for the blade fold pin which falls barely below the lower bound. This system is considered to be technically acceptable. However, because of the anticipated problems in recording data correctly in certain flight condition categories which were discussed in Section 3, the detailed definition and cost-effectiveness of this system will not be pursued.

Likewise, System 2 was tested by SIMULE, yielding predictions for each of the nine components shown in Table 15. The system was technically acceptable for the control horn, rotating swashplate, stationary swashplate, tail rotor hub assembly, tail rotor pitch actuating shaft and main rotor pushrod. However, the predictions for the blade fold pin, main rotor attachment bolts, and main rotor upper hub assembly were overly conservative, being below the lower bound. Other versions of System 2 were synthesized and tested but in each case, these three components were again treated in an overly conservative manner. Consequently, it was decided to determine the cost-effectiveness of System 2 with the assumption that only the six components for which acceptable predictions were made would be tracked.

TABLE 14. SIMULE PROJECTED LIFE COMPARISONS TO UPPER AND LOWER BOUNDS FOR SYSTEM 1

Component	Lower Bound	SIMULE Projected Life	Upper Bound
Blade Fold Pin	3459	3453	3699
Control Horn	941	3856	3863
Rotating Swashplate	981	1629	1787
Stationary Swashplate	1759	31502	31586
Tail Rotor Hub Assembly	8127	10206	10232
Tail Rotor Pitch Actuating Shaft	593	5224	5236
Main Rotor Blade Attachment Bolt	2210	2193	2286
Main Rotor Pushrod	18445	27669	27734
Main Rotor Upper Hub Assembly	7953	9543	10052

TABLE 15. SIMULE PROJECTED LIFE COMPARISONS TO UPPER AND LOWER BOUNDS FOR SYSTEM 2

Component	Lower Bound	SIMULE Projected Life	Upper Bound
Blade Fold Pin	3459	1512	3699
Control Horn	941	3802	3863
Rotating Swashplate	981	1755	1787
Stationary Swashplate	1759	30271	31586
Tail Rotor Hub Assembly	8127	10206	10232
Tail Rotor Pitch Actuating Shaft	593	5222	5236
Main Rotor Blade Attachment Bolt	2210	1260	2286
Main Rotor Pushrod	18445	27212	27734
Main Rotor Upper Hub Assembly	7953	1256	10052

5. SIRS SYSTEM DEFINITION

The SIRS (Structural Integrity Recording System) system consists of three discrete but interrelated subsystems. The airborne SIRS recorder monitors helicopter usage by identifying and storing the occurrences of various flight conditions. The ground-based, portable data retrieval unit monthly transfers the recorder-stored data onto a miniature data tape cassette. At a central data processing site such as the Naval Air Development Center, the data processing software system automatically processes and analyzes the data, and then generates tailored reports which present for each monitored helicopter its usage and the corresponding incremental fatigue damage of each component. The complete system is pictured in Figure 5.

5.1 Airborne Recording System

The airborne recording system consists of the SIRS recorder, complementary transducers, shock mount, mounting brackets and wiring harnesses. The typical installation weight is 20-24 pounds, depending upon the transducer complement.

5.1.1 SIRS Recorder

The SIRS recorder, viewed in Figure 6, incorporates a Motorola Model 6800 microprocessor. This microprocessor monitors the thirteen flight parameters listed in Table 16 and from them, calculates first the density altitude, adjusted airspeed limits, and rate of descent or ascent. When the flight parameters fall in preset ranges or form certain flight conditions, the microprocessor accumulates their occurrence or the amount of time associated with them in the recorder's memory. The flight conditions are defined generally as various combinations of flight parameters, each in a preset range or varying in a preset manner. Examples of flight conditions are flight time, rotor starts, and turns. Table 6 lists the 69 flight condition categories of System 2 established for the RH-53D helicopter in this study.

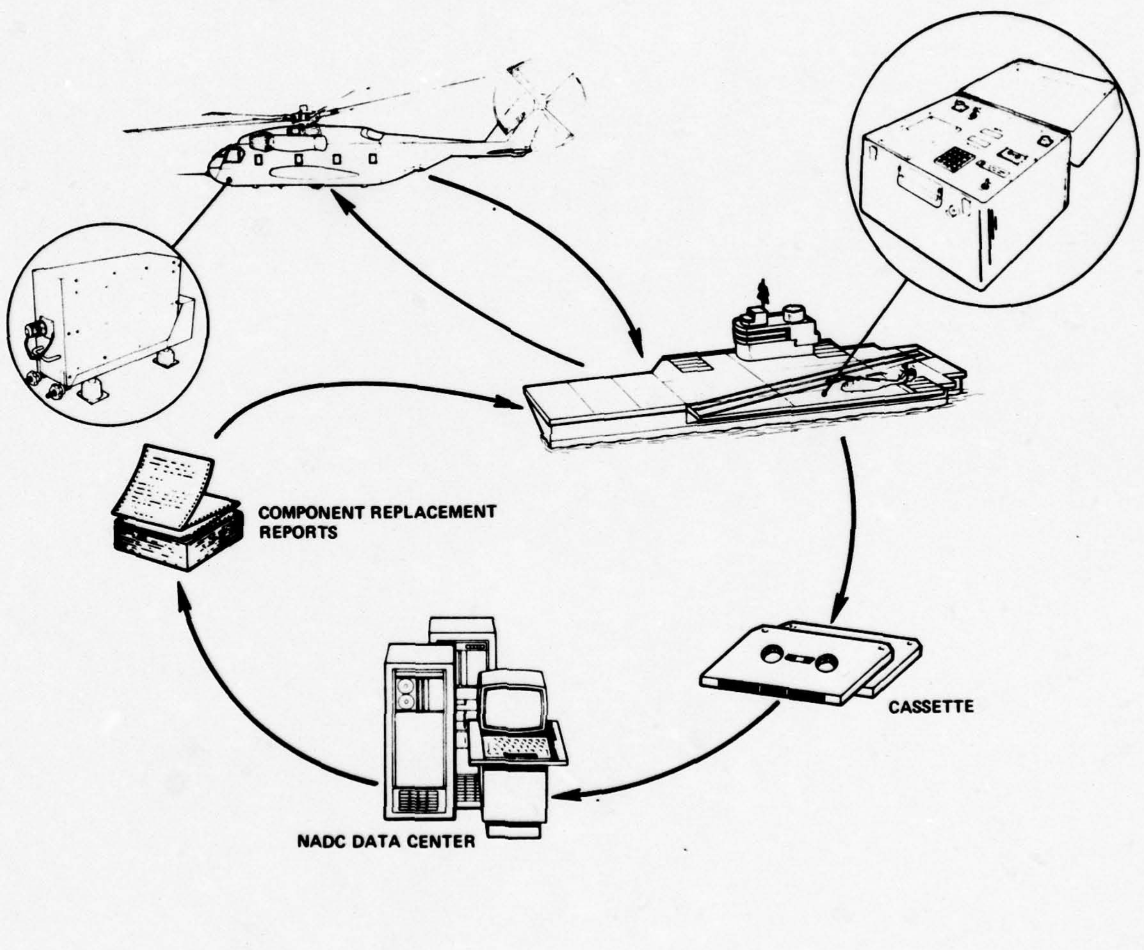

Figure 5. SIRS for the RH-53D Application

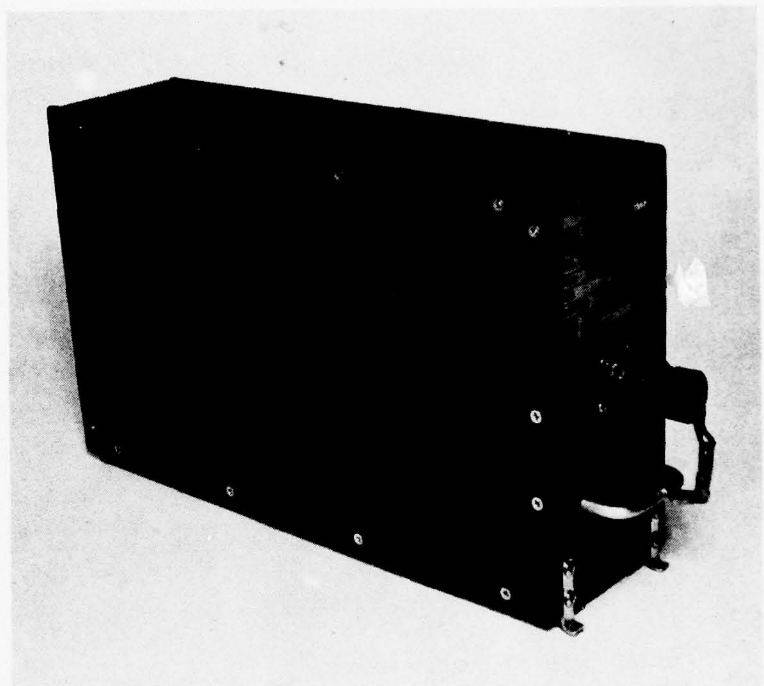

Figure 6. SIRS Recorder

TABLE 16. SIRS SYSTEM 2 PARAMETERS

Measured	Computed
Airspeed	Percent V_H Airspeed
Airspeed Direction	Density Altitude
Pressure Altitude	Rate of Climb
Radar Altitude	Rate of Descent
Outside Air Temperature	
Landing Gear Touchdown	
Pitch Attitude	
Roll Attitude	
Engine Torque	
Main Rotor Speed	
Vertical Acceleration	
Tow Tension	
Tow Angle	
Rudder Pedal Position	

As shown in Figure 7, the SIRS recorder processes the inputs from the transducers for the fourteen monitored parameters. Each of the inputs is conditioned to a desired full-scale signal level, multiplexed, and converted from an analog signal to a digital signal to be processed by the microprocessor. The recorder software logic identifies the flight conditions by associating the variation and corresponding time of each input parameter with those of the other input parameters. While these conditions are being identified, the microprocessor calculates the density altitude and limit velocity, and temporarily stores the results of these calculations in the recorder's scratch pad memory. The programs for these calculations and the flight condition software logic are contained in PROM (Programmable Read-Only Memory) integrated circuits. The time spent in or the number of occurrences of the various flight conditions is stored in the recorder's data storage memory, which is composed of RAM (Random Access Memory) integrated circuits. Since these circuits are volatile, the recorder incorporates a battery with a one-year operational capacity to retain the stored data when aircraft power is turned off.

5.1.2 Transducers

The fourteen monitored parameters of System 2 may be divided into two categories: those which require unique transducers and those which use aircraft subsystems. Table 17 presents these two categories.

5.1.2.1 Unique Transducers

The unique transducers include airspeed magnitude and direction, pressure altitude, outside air temperature, vertical acceleration, and rudder pedal position. Forward and lateral airspeed should be monitored using a low-airspeed system such as the one manufactured by Rosemount Engineering Company; lateral airspeed or direction will be used to identify

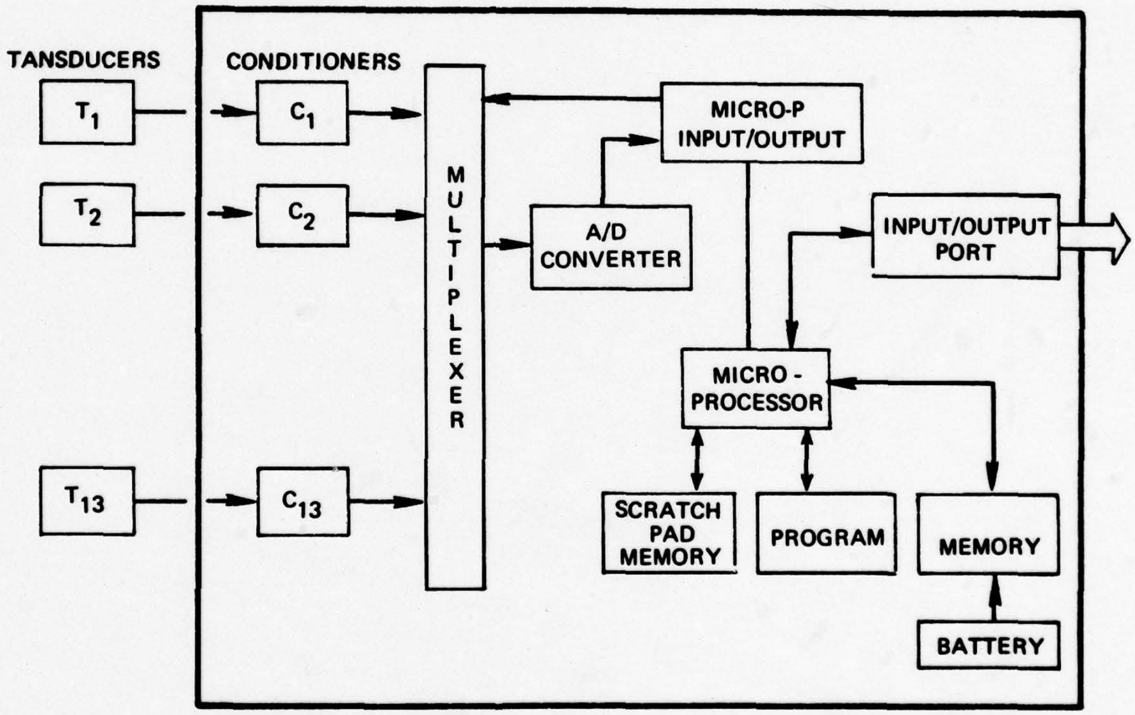

Figure 7. Schematic of the SIRS On-Board Recorder

TABLE 17. SIRS SYSTEM 2 PARAMETER MEASUREMENT TECHNIQUE

Parameter	Transducer Unique	Transducer Aircraft Subsystems
Airspeed	•	
Airspeed Direction	•	
Altitude	•	•
Outside Air Temperature	•	
Landing Gear Touchdown		•
Pitch Attitude		•
Roll Attitude		•
Engine Torque		•
Main Rotor Speed		•
Vertical Acceleration	•	
Tow Tension		•
Tow Angle		•
Rudder Pedal Position	•	

sideward or rearward flight while in a hover. Pressure altitude should be measured by an absolute pressure transducer similar to Rosemount Model 1332A3 (0 to 15 psia); the pressure altitude will be used to compute the V_H limit and rate of climb or descent. A resistance thermal ribbon embedded on a silicon rubber mount should be used to measure outside air temperature. Vertical acceleration should be measured by a -1 to +3g accelerometer such as a Columbia Research Laboratories Model SA109-B-1/+3 SL transducer. Finally, rudder pedal position should be measured by an angular or linear wire-wound potentiometer. Unique signal conditioning for each of these parameters would be included in the SIRS recorder.

5.1.2.2 Aircraft Subsystem Transducers

Those parameters which could use existing RH-53D subsystem instrumentation include radar altitude, landing gear touchdown, pitch attitude, roll attitude, engine torque, rotor speed, tow tension and tow angle. The radar altimeter would be used to support the identification of hover conditions. The existing main landing gear squat switch should be used to indicate takeoff/landing conditions. Output of the aircraft attitude indicating system should be used to acquire pitch and roll attitude information. The absolute value of pitch attitude will be required but discrimination between left and right roll attitude will not be required. Engine torque, likewise, can be acquired from the aircraft system. Main rotor speed should be monitored by converting the aircraft's main rotor tach generator frequency signal to a proportional voltage signal using the signal conditioning circuitry of the SIRS recorder. Tow tension and angle should be acquired from the aircraft's instruments. Unique signal conditioning for each of these parameters would be included in the SIRS recorder.

5.1.3 SIRS Recorder Software

As discussed earlier, the SIRS recorder contains software or logic routines which monitor the variations of the monitored parameters and identify the occurrence and/or duration of various flight conditions. As might be imagined, this software is the heart of the recorder because it allows the conversion of the real-time variation in the fourteen parameters into meaningful information, i.e., flight conditions, and allows for the economical storage of these data in the recorder's memory. It must be understood that if the on-board processing was not performed, then the volume of data collected would increase rapidly, resulting in the need for a much larger memory within the recorder and the need to retrieve data more frequently. In addition, more data processing at a ground-based data center would be required, thus resulting in higher operating costs.

Several examples of how the SIRS recorder identifies flight conditions will be presented below. Not all of the software routines will be discussed, but enough will be presented to provide a clear understanding of the operation of the recorder. In review, the monitored parameters listed in Table 17 will identify the flight condition categories of Table 6 for System 2 using the relationships presented in Table 3. It should be noted that System 2 does not contain longitudinal, lateral, or collective slide positions, but this will not detract from the ability or efficiency of the SIRS recorder to identify the required flight conditions.

Rotor starts are identified by the increase of rotor speed from zero to above the threshold level for ground idle. The exact level or value of rotor speed varies from aircraft type to aircraft type. A "flag" is set when rotor speed crosses the threshold and stays above the threshold for some period of time. When the rotor speed goes

below the threshold, a count is added to the memory location, indicating a rotor start/stop cycle has occurred.

Likewise, a takeoff and landing is considered to be a single occurrence of the landing gear touchdown indicator going from the "ground" position to the "air" position, and back to the "ground" position. In this case, however, the presence of rotor speed in the flight range must occur concurrently with the flight portion of the landing gear indication, and certain timing conditions must be satisfied. These timing conditions are necessary to prevent multiple takeoffs and landings from being counted under such conditions as the helicopter's being "light on its gear" prior to takeoff or the helicopter's bouncing on its landing gear during a hard landing.

Hover conditions are identified by the simultaneous occurrence of being in-flight, being at a low altitude, and having the airspeed parameter at zero or low. Hovering turns would satisfy these conditions steadily while variations occur in rudder pedal position. Sideward flight is differentiated from hover by the magnitude of sideward velocity; consequently, hovering in wind conditions perpendicular to the longitudinal axis of the helicopter would be treated as though the helicopter was in sideward flight under zero wind conditions.

Climbs are identified by the increase of altitude and are separated into the two FCC classes of "Climb at Military Power - FCC 42" and "Climb at Full Power - FCC 43" by the range of the combined engine torque. Likewise, descents are categorized as partial power or autorotation and classed by their velocity and rate-of-descent.

Level flight conditions must satisfy the condition of altitude being constant or nearly constant and engine torque

being within certain ranges. Time in level flight is then categorized into the appropriate flight condition category by the range in which airspeed is and by the range in which main rotor speed is. Although Table 6 divides level flight conditions into one of two main rotor speed ranges, the hardware implementation of System 2 would divide the ranges into less than 98%, 98-102%, 103-106% and greater than 106%. These extra divisions would provide more clarity to the acquired data. Rudder reversals occurring during level flight would be categorized based upon airspeed and would have certain time relationships to satisfy. Turns are identified by roll attitude going outside of threshold for a minimum period of time and a vertical acceleration peak above a certain threshold occurring during the period that roll attitude is outside of the threshold. It is not necessary that every turn be captured by the SIRS recorder but every moderate to severe turn should be captured. Consequently, the occurrence of a vertical acceleration peak during the turn is a requirement which must be satisfied. FCC's 53 and 54 would be broken into more flight condition categories in practice to allow for the turns to be categorized by concurrent ranges of airspeed, vertical acceleration, and roll attitude. Autorotation flight conditions are similar to power-on flight conditions described above except for the value of engine torque.

The approach to landing, either normal or rough, is discerned by first identifying a steady descent, monitoring the radar altimeter indications of altitude and engine torque to capture the period of the approach and flare to landing. Touchdown need not occur. Classifying the time spent in approach as either normal or rough depends on the vertical acceleration range during the maneuver.

Towing would be monitored by System 2 in a more comprehensive manner than just left or right. During steady

towing, data would be stored in ranges of tow tension by towing angle left or right. In addition, towing turns would be identified. Periods of streaming or recovering towing equipment would be covered by low-speed flight or hover.

Finally, the GGAG cycles would be recorded by storing temporarily the coded names for the maneuvers associated with the highest and lowest loads. Only one set of names or FCC numbers would be stored for each cycle within the recorder memory. Alternately, should this not prove feasible, then the GGAG cycle would be treated as always being the maximum cycle used in the original fatigue analysis and the frequency of occurrence would be based upon the number of takeoffs and landings.

Several additional flight condition categories should be included in System 2 although not specifically required by the fatigue damage assessment model. These include histograms of altitude, engine torque and main rotor speed during flight; the time distributions of each of these parameters are helpful in interpreting the acquired data. Also, the number of occurrences for each flight condition category of turns should be stored in the recorder's memory. Finally, the number of vertical acceleration peaks in various ranges of g's should be recorded. Through previous experience, all of these data have been found to be useful in supplementing the qualitative analysis of the collected data; none of them are needed for the quantitative analysis of the data by the SIRS data processing software.

5.2 Ground-based Retrieval Unit

The airborne SIRS recorder is designed so that data need be retrieved only once a month by a portable, flight-line data retrieval unit pictured in Figure 8. During the transcription of the recorder data onto the miniature magnetic

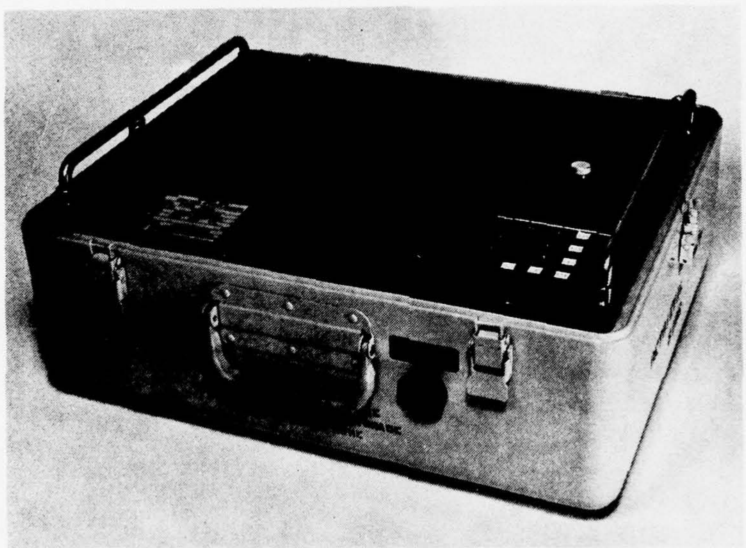

Figure 8. SIRS Retrieval Unit

tape cassette, the operator interacts with the unit. While the unit presents messages on a LED display, the operator communicates with the unit through a keyboard. Because of the on-board processing of the flight data, the data recorded during the normal monthly operation of more than 50 helicopters can be stored on a single data cassette. The data retrieval, including set-up, takes less than 5 minutes and can be performed on a flexible schedule. In addition to data retrievals, the data retrieval unit performs diagnostic checks of the recorder, on-board recorder battery, and transducers. It can also be used as a read-out device during transducer calibration.

During the retrieval process, limited operator inputs listed in Table 18 are requested to supplement data contained within the recorder. The aircraft serial number is entered in the format of fiscal year and aircraft number, xx-xxxxx, and supplements the recorder serial number, which is permanently stored electronically within the recorder. Since retrievals are not performed on a fixed schedule, the retrieval data, in the format of day, month, and year, is another entry; this information is used to establish trends in the retrieved data. The chronology of the data is identified by a numbering device built into the recorder which increments each time a retrieval is made. Logbook flight hours are entered to track the variation between the actual flight and ground operating time and the logged time. The operating base is entered to permit analyzing the fleet-wide variation in helicopter usage. Finally, as requested by the display, the operator enters the reason for data retrieval. There are three acceptable reasons: monthly retrieval, component replacement, and recorder maintenance. After the operator enters the supplemental data, the data retrieval unit performs a diagnostic check of the recorder including its memory, makes a copy of the recorder data residing in memory, and records the current static values of each of the transducers.

TABLE 18. SIRS RETRIEVAL UNIT OPERATOR INPUTS

Aircraft Serial Number	Base of Operation
Date of Retrieval	Reason for Retrieval
Log Book Flight Hours	

These data, together with the supplemental data previously entered by the operator, are recorded on the miniature magnetic tape cassettes. Each time the data are transferred, that is, from the memory in the recorder to that in the data retrieval unit and from the latter to the cassette, the data are checked to verify the validity of the transfer.

The various error messages listed in Table 19 are displayed when the diagnostics check detects recorder deficiencies, when the data cannot be retrieved or written on the tape cassette, or when the tape cassette is not installed or is full. Each coded error message (instructions for each are mounted inside the cover of the data retrieval unit) leads the operator to the necessary corrective action.

The data retrieval unit is 19.1 inches long, 15.6 inches wide, and 9.8 inches high. It weighs 45.4 pounds. Containing its own rechargeable power system, the retrieval unit is housed in a flight-line styled container. The recharging power required is 110 to 120 VAC, 60 Hz.

5.3 Data Processing Software

Upon receiving the data from the miniature cassettes, the software system first performs an initial data processing (1) to verify the recorder operation and transducer functioning and (2) to review the long-term trend of the transducer static readings; it then analyzes the data. The data analysis includes the data segregation by specific flight condition categories, the data conversion to a 100-flight hour basis, and the data presentation in terms of a usage spectrum. An example of this data presentation is shown in Figure 9. Next the software system governs three techniques to further analyze the data by calculating the incremental fatigue damage for each critical tracked component. The first technique is based on the relationship of the recorder data with the SIRS fatigue model developed for the RH-53D helicopter. In the

TABLE 19. RETRIEVAL UNIT ERROR MESSAGES

LINE ABORT?	-	Denotes that the retrieval unit to recorder communications were not properly established or were interrupted.
DATA ABORT?	-	Denotes that there was an error condition during the transmission of the recorder data onto the retrieval unit's temporary data-storage memory.
WRITE ABORT?	-	Denotes that there was an error condition during the data writing on the magnetic tape.
FULL ABORT?	-	Denotes that sufficient space could not be found on the magnetic tape for the data writing.
TAPE ABORT?	-	Denotes that the tape cassette is not capable of reading or writing because of its malfunctioning or improper positioning.
COUNTER	-	Denotes that a bad memory location was detected during the diagnostic check of the recorder's data-storage memory.
BATTERY	-	Denotes that the recorder's battery power supply is marginal.

SIRS SPECTRUM USAGE

AIRCRAFT: 67-15524 LOG TIME: 1985.6 HOURS RETRIEVAL DATE: 050678
RECORDER: 1030 BASE: 1 REASON: SCHEDULED
DELTA LOG TIME: 1.0 HOURS
DELTA RECORDER TIME: 0.9 HOURS
VALUES PER 100 HOURS WERE COMPUTED USING RECORDER TIME

FCC NUMBER	FLIGHT CONDITION	TIME (HOURS) RETRIEVAL	TIME (HOURS) PER 100 HRS	OCCURRENCES RETRIEVAL	OCCURRENCES PER 100 HRS
	FLIGHT TIME TOTAL	0.90	100.00		
01	ROTOR CYCES			1	111.1
02	TAXI TURNS TOTAL	0.00	0.00		
04	HOVER 100% NR	0.10	0.10		
05	HOVER 105% NR	0.20	0.22		
	LEVEL FLIGHT TOTAL	0.70	0.78		
06	20%VH 100%NR	0.15	0.17		
07	20%VH 105%NR	0.20	0.22		
08	40%VH 100%NR	0.00	0.00		
09	40%VH 105%NR	0.30	0.33		
10	50%VH 100%NR	0.00	0.00		
11	50%VH 105%NR	0.05	0.06		
12	60%VH 100%NR	0.00	0.00		
13	60%VH 105%NR	0.00	0.00		
14	70%VH 100%NR	0.00	0.00		

Figure 9. Sample of Usage Spectrum Generated by SIRS Data Processing Software

COMPONENT DAMAGE

AIRCRAFT: 67-15524 LOG TIME: 1985.6 RERIEVAL DATE: 050678
RECORDER: 1030 BASE: 1 REASON: SCHEDULED
DELTA LOG TIME: 1.0 HOURS
DELTA RECORDER TIME: 0.9 HOURS

COMPONENT	SIRS DAMAGE	FLIGHT HOUR DAMAGE RECORDER	FLIGHT HOUR DAMAGE LOG
CONTROL HORN	0.00072	0.00080	0.00091
ROTATING SWASHPLATE	0.00035	0.00027	0.00030
STATIONARY SWASHPLATE	0.00000	0.00009	0.00010
TAIL ROTOR HUB	0.00002	0.00013	0.00015
T/R PITCH ACTUATING SHAFT	0.00009	0.00040	0.00045
MAIN ROTOR PUSHROD	0.00007	0.00008	0.00009

Figure 10. Sample of Component Damage Generated by SIRS Data Processing Software

second technique the calculations are based on the rates established by current Navy-approved component replacement times and the logbook flight hours. The third technique is the same as the second except that the recorder flight time is used instead of the logbook flight time. Figure 10 is a sample of the format used in presenting the data calculated by each technique.

5.4 Pilot Program Definition

In order to estimate the developmental costs of applying SIRS to U.S. Navy helicopters, for use in the life cycle cost analysis, a pilot program outlining the activities necessary is defined in this section.

SIRS has been extensively flight tested as part of the U.S. Army development contract, DAAJ02-75-C-0050, to verify its ability to recognize and store the occurrence of various typical flight conditions. Consequently, the pilot program for the U.S. Navy should concentrate on the application of the SIRS recorder to the RH-53D helicopter, that is, verifying its performance in terms of aircraft interface compatibility and recorder software adequacy. Also, the U.S. Navy pilot program should further the reliability demonstration of the SIRS recorder by additional testing.

In particular, the pilot program should consist of a twenty-hour flight test program in which the operation of the SIRS recorder would be validated and the threshold levels used by the SIRS software would be refined. During the flight test program, the performance of the SIRS recorder would be monitored by two parallel analog recording systems. The first system would record the various SIRS parameter levels that trigger the logic routine operations and consequently provide the data needed to verify the functioning of the logic routines of the SIRS software. The second recording system would record the parameters listed in Table 20

TABLE 20. RECOMMENDED FLIGHT TEST PARAMETERS FOR FCR RECORDING SYSTEM

Airspeed	Longitudinal Stick Position
Airspeed Direction	Lateral Stick Position
Pressure Altitude	Collective Position
Radar Altitude	Rudder Pedal Position
Outside Air Temperature	Tow Tension
Vertical Acceleration	Tow Slew Angle
Pitch Attitude	Time
Roll Attitude	Reference Voltage
Engine Torque	
Main Rotor Speed	

needed to process the data using the FCR (Flight Condition Recognition) technique. This method of processing would allow the various flight conditions to be identified. Both recording systems would be run in parallel so that the ability of the SIRS recorder to identify flight conditions could be verified by comparing the first recording system showing SIRS software operations with the second recording system identifying the flight condition being flown. The flight test program would investigate all of the flight conditions critical to the fatigue substantiation of the RH-53D dynamic components, and would also investigate normal operational flights. The first portion of the flight test is somewhat obvious. Each of the flight conditions critical to the fatigue substantiation of the RH-53D dynamic components would be flown to verify that the SIRS recorder can identify the condition and store the appropriate amount of time for that flight condition in the appropriate location of memory. The second portion of the flight test program would consist of monitoring several normal operational flights. The reason for this testing may need some explanation. Experience with SIRS and oscillograph recording programs in general has identified the situation in which helicopters are operated in a manner significantly different from that which would be expected by the helicopter manufacturer. Certain cases have been identified where the parameter thresholds established for SIRS are such that incorrect recording would occur due to the manner in which the helicopters are flown. Consequently, the second portion of the flight test program should consist of several normal operational missions conducted by the instrumented RH-53D helicopter to determine if any anomalies exist within the SIRS recorder or its software.

Data collected during the flight test program would be processed, each in its own manner. The data from the first system would be processed by identifying the parameter levels and the logic routines that were triggered. The durations

or occurrences of these flight condition categories would be identified. The data from the second system would be processed using the FCR techniques, thus identifying each of the flight conditions flown and the duration of the flight condition. Then these data would be compared to identify the ability and accuracy of the SIRS recorder to record the experienced flight conditions. During the original U.S. Army development flight test, it was found that this method was entirely adequate and quite simple to accomplish.

Following the successful completion of the flight test program, the pilot program should move into its second phase. During this phase, five RH-53D helicopters would have the SIRS recording system installed. Operational usage data would be collected for a six-month period; this collection effort would be used to demonstrate the ability of the system to collect operational usage data in a non-flight test environment. A preliminary statement of work for the flight test portion of the pilot program is included in Appendix A.

The third phase of the pilot program should consist of the reliability qualification testing of the SIRS recorder. During the U.S. Army sponsored development program, a reliability model of SIRS was constructed and a preliminary predicted Mean-Time-Between-Failure (MTBF) was calculated. Using the procedures outlined in MIL-STD-785, the MTBF was calculated to be 7300 hours. Testing to substantiate this prediction was not part of the U.S. Army program, although environmental testing in accordance with MIL-STD-810 was accomplished. Operational experience to-date has supported the predicted MTBF, although not enough experience has been obtained to quantitatively substantiate the MTBF. Consequently, a more rigorous substantiation of the MTBF in accordance with the reliability qualification test requirements of MIL-STD-781C, Category 5 should be conducted to support the application of SIRS on U.S. Navy helicopters.

6. LIFE-CYCLE COST ANALYSIS

The viability of SIRS cannot be solely based upon its ability to monitor the usage of helicopters and to relate that usage to its effect on the helicopter's fatigue-critical dynamic components. SIRS must accomplish this monitoring process in a cost-effective manner. The anticipated savings associated with extended component usage obtained through the use of the SIRS recorder are the reduction in component cost and the reduction in man-hours associated with the replacement of these components. To estimate this cost, Navy 3M data was examined to determine the costs associated with the scheduled replacements of the selected components. With the introduction of SIRS, these scheduled replacements would be delayed to the extended life limits predicted by SIMULE for System 2.

A U.S. Army-developed life-cycle cost model (Reference 13) was used to project the break-even point between the added costs of incorporating SIRS and the savings anticipated through extended component usage. This model was developed to perform economic analyses on Product Improvement Proposals (PIP) and Engineering Change Proposals (ECP). The model computes the cost savings or penalties associated with the PIP/ECP, in this case, the incorporation of SIRS, over any time period and computes the time required to reach the break-even point.

6.1 Model Description

SIRS is being justified on the belief that, over a period of time, the costs of its installation, maintenance and the monthly data processing will be compensated for by the savings in operating costs so that the life-cycle cost with SIRS is less than that of the current system.

To briefly explain the theory upon which the model is based, Figure 11 presents an idealized situation for the incorporation of SIRS. The curve I represents the cumulative

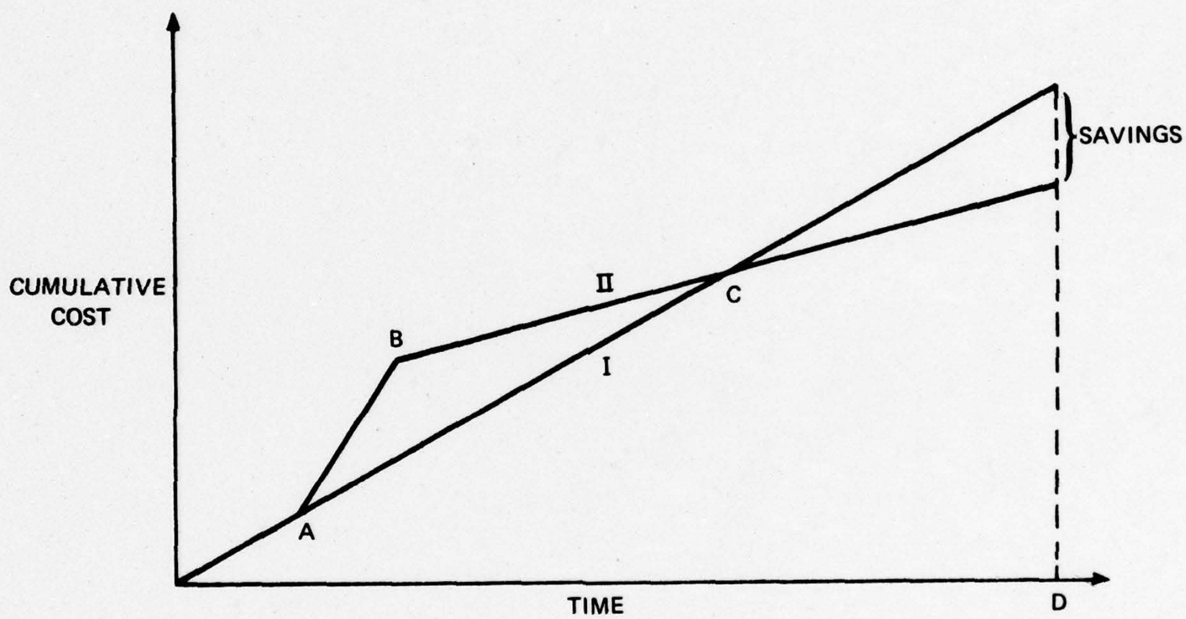

Figure 11. Cumulative Cost of SIRS versus Time

cost of operating the fleet of helicopters by removing the critical components at preset times. The curve II represents the cumulative costs of incorporating SIRS and operating the fleet with extended component replacement times. The steeper slope of curve II between Points A and B represents the increased rate of expenditure due to implementation. Point B marks the point where the implementation of SIRS is completed. The reduced slope of curve II after point B represents the reduced operating costs with SIRS. Point C is the breakeven point where the savings from the reduced operating costs exactly compensate for the cost of implementation. Point D represents the end of the system's life.

The basic scenario assumed by the model is as follows: The SIRS recording system is proposed to permit the life-limited components to be used for an extended period. The SIRS system will allow the components to last longer but will require its own preventive maintenance. The incorporation of SIRS on each helicopter will be accomplished by using a retrofit kit which will include a recorder, transducers, brackets and wiring. These kits will be installed at a rate of ten percent of the initial fleet per month. Included in the analysis is the cost of maintaining the SIRS system, the cost of processing the monthly data, and the cost of replacing the life-limited components. Although the model has the feature of including the cost related to an aircraft lost due to component failure, this feature has not been included in the current analysis. The input parameters for the model are summarized in Table 21.

Because SIRS affects each life-limited component to a different extent, the cost analysis was performed separately for each component. Consequently fixed and variable SIRS costs were divided among the six components being monitored by System 2. The cost effectiveness of the SIRS system was determined by summing the results of the individual components.

TABLE 21. COST MODEL INPUT PARAMETERS

1. Strategy for kit implementation
2. Number of months under evaluation
3. Number of aircraft in the fleet
4. Aircraft attrition rate
5. Maximum utilization rate
6. Simple annual discount rate
7. Non-recurring SIRS cost
8. Number of items per aircraft
9. Total aircraft scheduled for retrofit in field
10. Total aircraft scheduled for retrofit at depot
11. Purchase cost per retrofit kit
12. Shipment cost per retrofit kit
13. Manhours to install one kit in field
14. Manhours to install one kit at depot
15. Mean time between failure without SIRS
16. Purchase cost of component
17. Shipment cost of component
18. No. of manhours to replace component
19. Fraction of replacements of components done at depot (all replacements not done in depot done in field)
20. No. of components in stockpile inventory
21. Mean time between failure with SIRS
22. Purchase cost of component (same as 16)
23. Shipment cost of component (same as 17)
24. No. of manhours to replace component (same as 18)
25. Fraction of replacements of components done at depot (same as 19)
26. Preventative maintenance requirement of component
27. Preventative maintenance requirement of SIRS
28. Monthly cost of processing SIRS data
29. Cost per manhour in the field
30. Cost per manhour at the depot
31. Aircraft lost without SIRS
32. Aircraft damaged without SIRS
33. Fleet flying hours during period in which crash occurred
34. Average aircraft crash loss value
35. Average aircraft crash damage value
36. Strategy of retrofit implementation

6.2 Input Data

In the previous section, the input parameters for the cost analysis were highlighted. In the following paragraphs, the derivation of each input parameter will be presented. To set the conditions assumed by the analysis, it was assumed that the fleet size could be 100, 200 or 400 aircraft, no aircraft were lost in crashes, all retrofit kits were installed in the field, and all components were replaced in the field. Costs related to components were obtained from NAVAIR (Reference 12) and the costs related to SIRS were estimated by Technology Incorporated on the basis of previous programs.

6.2.1 Strategy for Kit Implementation

It was assumed that all of the kits would be installed in the field and none at depot.

6.2.2 Number of Months under Evaluation

The program uses a period of 155 months for the cost evaluation but the data presented in this analysis is for two periods, 60 months and 120 months. These two periods were picked to show the short- and long-term cost-effectiveness of SIRS.

6.2.3 Number of Aircraft in the Fleet

Three fleet sizes of 100, 200 and 400 aircraft were used to evaluate the effect of fleet size or cost effectiveness.

6.2.4 Maximum Utilization Rate

Twenty-five hours of flight per month was the assumed rate.

6.2.5 Simple Annual Discount Rate

The preset program value for the discount rate is 10 percent.

6.2.6 Nonrecurring SIRS Cost

The estimated nonrecurring cost of adapting the SIRS system to U.S. Navy helicopters, including design, testing, training, manuals and special test equipment, was $395,000. On a per component basis, the cost of $65,800 was used in the analysis.

6.2.7 Number of Items per Aircraft

Table 22 presents the number of each component installed on the RH-53D helicopter.

6.2.8 Purchase Cost of Retrofit Kit

The per component cost of the retrofit kit is $1975. This is based upon a recorder price of $5000, an installation kit price of $4850 and an apportioned price of $2000 for the retrieval unit. It is assumed that the ratio of recorders to retrieval units will be six to one.

6.2.9 Shipment Cost of Retrofit Kit

Based upon a shipping rate of $43.96 per 100 pounds and a kit weight of 30 pounds, the per component cost will be $2.20.

6.2.10 Manhours to Install One Kit in the Field

Using previous installations as guidelines, it is estimated that it will take 84 manhours to install one kit.

6.2.11 Mean-Time-Between-Failure without SIRS

For each component, this time is the lower bound or current NAVAIR replacement time, assuming that the flight restrictions were not in effect; these times are presented in Table 1.

TABLE 22. COMPONENT INPUT DATA

Component	No. per Aircraft	Cost	Shipping Weight	Manhours to Replace
Control Horn	6	$700	10	1
Rotating Swashplate	1	14,000	350	202
Stationary Swashplate	1	8,000	122	210
Tail Rotor Hub	1	6,000	86	16
Tail Rotor Pitch Actuating Shaft	1	2,000	10	36
Main Rotor Pushrod	6	2,000	4	2

6.2.12 <u>Purchase and Shipment Cost of Components</u>

The purchase cost of each component is presented in Table 22. The shipment cost of each component was computed based upon a shipping rate of \$43.96 per hundred pounds up to 500 pounds and \$30.27 per hundred pounds up to 2000 pounds; the shipping weight of each component is presented in Table 22.

6.2.13 <u>Number of Man-Hours to Replace a Component</u>

These data are presented for each component in Table 22.

6.2.14 <u>Number of Components in Stockpile Inventory</u>

This number was assumed to be zero since the new and old components are the same and, consequently, no spares will be obsoleted.

6.2.15 <u>Mean-Time-Between-Failure with SIRS</u>

For each component, this time is assumed to be the SIMULE projection shown in Table 15.

6.2.16 <u>Preventive Maintenance Requirement of Component</u>

This value was assumed to be equal to zero since it is not anticipated that the component inspection cycle would be changed if SIRS was incorporated.

6.2.17 <u>Preventive Maintenance Requirement of SIRS</u>

The preventive maintenance required by the SIRS system was computed on the basis of MTBF's of 7272 hours for the recorder, 1394 hours for the transducers, and 5000 hours for the retrieval unit; a flying hour rate of 300 hours per year; an average repair cost of \$1354 for the recorder, \$785 for the transducers and \$1354 for the retrieval unit; and a field man-hour rate of \$56.95 per hour. The repair costs for each item were divided by the rate of \$56.95 to convert

the costs to equivalent man-hours. These man-hours were then adjusted based upon the individual MTBF's and then summed; the summed rate was 0.000045 man-hours per flight hour. Dividing by six components, the final rate was 0.000008 man-hours per flight hour.

6.2.18 Monthly Cost of Processing SIRS Data

The monthly cost of processing SIRS data contained on cassettes was computed based on the number of cassettes to be processed each month, the man-hours required per cassette, and the cost of the NADC computer to process the data utilizing the data processing software. Since the SIRS data are blocked in terms of time spent in or occurrences of various flight conditions, the amount of data to be processed each month depends on the number of helicopters and not the number of hours which they fly. As discussed earlier, data from 25 helicopters would be placed on each cassette; consequently, for the three fleet sizes of this study, 4, 8, or 16 cassettes would be processed each month. Based upon cost data supplied by NADC for its computer and based upon Technology Incorporated's experience on the man-hours required to support the processing of each cassette, the cost of processing each cassette each month would be $268 or $3216 per year. Therefore, for the 100-aircraft fleet, the cost would be $12,864 per year.

6.2.19 Cost per Man-Hour in the Field

A rate of $56.95 was applied to each field man-hour.

6.2.20 Strategy of Retrofit Implementation

A preset schedule of 10% of the original fleet was set as the monthly incorporation rate in the field. All of the kits would be installed by the end of the tenth month.

6.3 Cost Analysis Results

Using the model described above, the effect of SIRS on three different RH-53D fleet sizes was evaluated. Sizable savings would be realized by using SIRS for any of the three fleet sizes. These savings are shown graphically in Figure 12

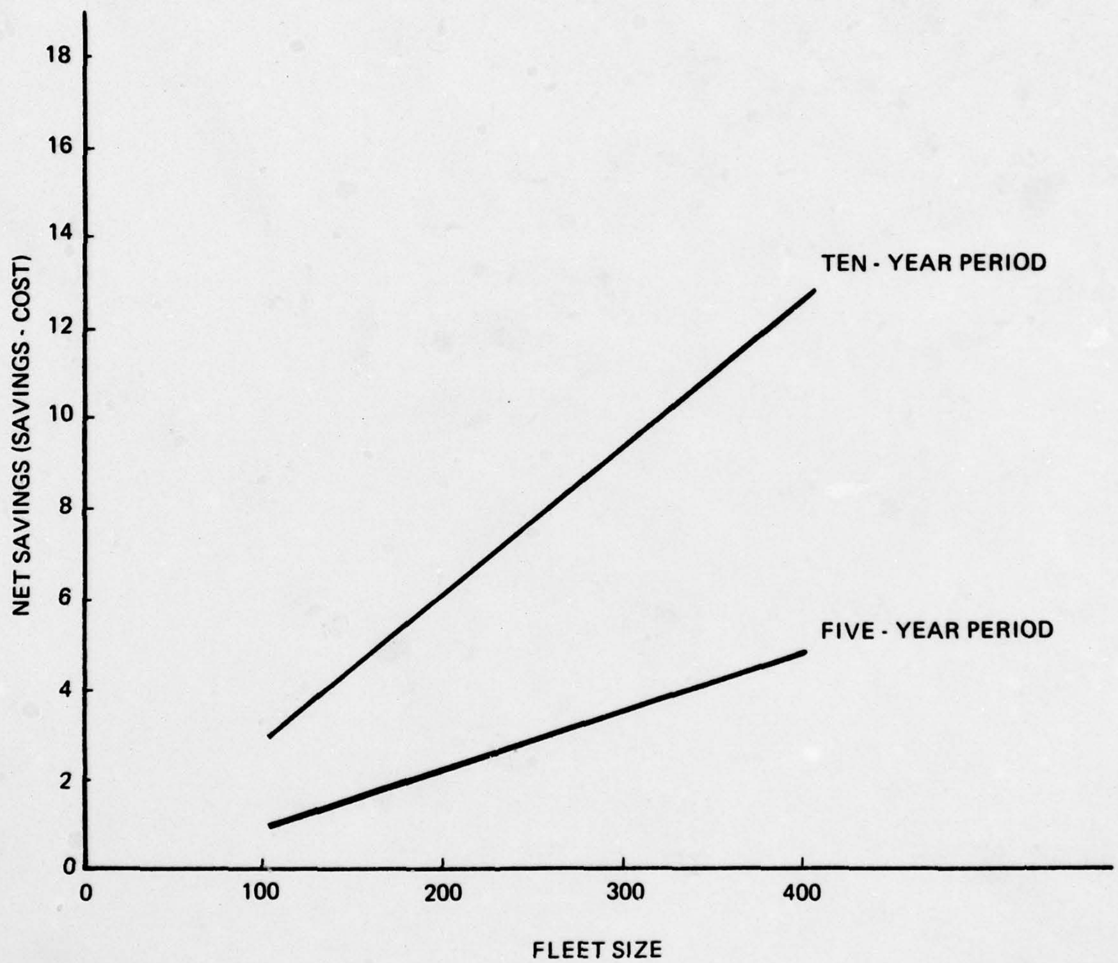

Figure 12. Net Savings Resulting from SIRS versus Fleet Size

TABLE 23. PROJECTED SAVINGS RESULTING FROM SIRS USE

Fleet Size	5-Year Period	10-Year Period
100 Aircraft	922,025	2,892,328
200 "	2,215,990	6,161,306
400 "	4,865,711	12,816,877

where the five-year savings would range between one million and five million dollars, whereas the ten-year savings would range between three million and thirteen million dollars; these savings are tabulated in Table 23.

The major portion of these projected savings would be realized by the increased use of the rotating and stationary swashplates and the tail rotor pitch actuating shaft. As can be seen in the individual summary sheets presented in Appendix B, these three components realized large savings after consideration was given to their share of the cost of implementing and maintaining SIRS. This was not the case for the control horn, tail rotor hub, and main rotor push-rod. In no case was a saving projected as a result of the implementation of SIRS for these components. This lack of

savings can be attributed to the low cost of the control horn, and the relatively high value of the lower bound lives of the tail rotor hub and main rotor pushrod.

In evaluating the cost-effectiveness of SIRS, the return on initial investment was determined. This value is important because of concern over the length of time it takes to recover the initial investment by the expected savings. Table 24 presents the initial investment for each of the fleet sizes investigated in this study and the projected net savings for both the five-year and ten-year period. As can be seen, SIRS does not create net savings in excess of its initially required investment during the first five years. This is due to the low-flying-hour program currently in effect and used in this study. However, in ten years, the net savings expected from using SIRS exceeds the initial investment, as shown in Table 25. Interpolating the data presented in these tables produces an expected period of 7-3/4 years for the 100-aircraft fleet and 6-1/3 years for the 400-aircraft fleet to accrue savings equal to the initial investment.

Based upon the results of this cost analysis, the System 2 version of SIRS will be cost-effective and will produce a savings of over 1 million dollars during the first five years of operation of a 100-aircraft fleet. Furthermore, with SIRS installed, the existing flight restrictions could be safely removed.

TABLE 24. RETURN ON INVESTMENT OF SIRS DURING FIRST FIVE YEARS

Fleet Size	Initial Investment	5-Year Savings	Return on Investment
100 Aircraft	2,059,700	922,025	45%
200 "	3,724,400	2,215,990	59%
400 "	7,053,800	4,865,711	69%

TABLE 25. RETURN ON INVESTMENT OF SIRS DURING FIRST TEN YEARS

Fleet Size	Initial Investment	10-Year Savings	Return on Investment
100 Aircraft	2,059,700	2,892,328	140%
200 "	3,724,400	6,161,306	165%
400 "	7,053,800	12,816,877	182%

7. SUMMARY AND CONCLUSIONS

In an effort to determine the feasibility of applying the U.S. Army-developed SIRS recording system to U.S. Navy helicopters, a study was conducted into the specific application of SIRS on the RH-53D helicopter. A fatigue damage assessment model was formulated for nine fatigue-critical dynamic components of the RH-53D helicopter, and two possible flight condition monitoring systems were synthesized. Both systems were found to be technically acceptable, but only one was practical based on current recording technology. The resulting system was anlyzed from a life-cycle cost viewpoint and found to be cost-effective. Savings equal to the original investment would be realized in 6 to 7 years, depending on fleet size. A pilot program outlining the activities necessary to demonstrate the conclusions of the study, that is, to demonstrate the application of SIRS on the RH-53D helicopter, was outlined. By the results of the foregoing analysis, it has been concluded that SIRS configured as System 2 can provide an acceptable means of monitoring dynamic component fatigue damage of U.S. Navy RH-53D helicopters from both technical and cost standpoints and that this application of SIRS should be demonstrated on the RH-53D helicopter.

8. RECOMMENDATIONS

It is recommended that the application of SIRS to the RH-53D helicopter be demonstrated through the performance of the pilot program defined herein.

APPENDIX A

NAVY SIRS FLIGHT TEST PILOT PROGRAM

Statement of Work

Navy SIRS
Flight Test Pilot Program

1.0 Background

The current practice of establishing overhaul and retirement lives for fatigue critical components on helicopters is less than adequate in that it dictates removal after a set number of flight hours based on anticipated loads, conservative design allowances and limited structural testing. These criteria are necessarily conservative and result in premature removal and early retirement of components before the useful life is expended. Under Contract DAAJ02-73-C-0053 with the U.S. Army, Technology Incorporated evaluated various monitoring concepts to define a more realistic basis for monitoring fatigue critical components in helicopters. To further the concepts under Contract DAAJ02-75-C-0050, a recorder and retrieval unit were developed and qualified for recording flight condition data on UH-1 helicopters. The success of this program has developed considerable interest in application of this recorder to other helicopters. Under Contract N00019-77-C-0318, Technology Incorporated is performing a study to define the application of the system to an RH-53D helicopter, the cost effectiveness of the system for that helicopter, and the definition of a demonstration program. The program defined in this statement of work is the demonstration program required to verify the effectiveness of the recording system for RH-53D helicopters.

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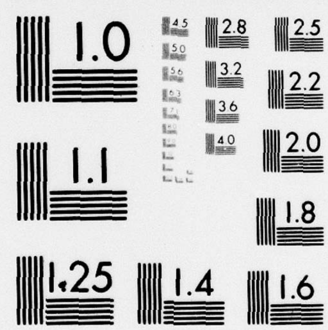

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU

2.0 Statement of Work

A program to demonstrate that the SIRS recorder modified for the RH-53D helicopter monitors actual usage and assigns damage properly needs to be accomplished. This program will include modification of the recorders, flight testing to verify operation, and an operational survey to collect an appropriate data sample.

2.1 Recording System Modification

Using the list of parameters to be acquired and the flight conditions identified under the study program, the SIRS recording system will be modified.

2.1.1 Hardware Modification

Design the SIRS recorder and retrieval unit modifications as required to record the flight conditions as defined in the study. Fabricate one recorder and one retrieval unit with these changes. Through analysis, verify that the ability of the recorder to operate in the specified environments has not been compromised by the modifications.

2.1.2 Software Modification

Modify the recorder and retrieval unit software in accordance with the flight condition monitoring criteria developed in the study.

2.1.3 Testing

Using test equipment which simulates the transducer inputs, test the recorder and retrieval unit to verify performance to the flight condition monitoring definition.

2.2 Flight Test

A detail flight test will be conducted to validate the operation of SIRS recording system including data acquisition operation and refinement of threshold levels. The flight test shall be conducted on a Government-furnished RH-53D helicopter. The flight test will include a minimum of twenty (20) hours of flight wherein data are recorded concurrently by the SIRS recorder and two oscillographs. The parameters monitored by the SIRS recorder will include but not be limited to indicated airspeed, altitude, vertical acceleration, roll rate, main rotor rpm, engine torque, tow tension, tow angle, and landing gear touchdown.

2.2.1 Oscillograph System

To verify that the recorder is recording flight conditions as they occur, a parallel analog recording system is required. This recording system is to be installed with the SIRS recorder and record as many of the same parameters as is necessary to validate the recorder operation. Also to

2.2.1 Oscillograph System (continued)

be recorded are events which signify when the SIRS recorder has identified a flight condition.

2.2.2 Installation Design

Design an installation kit that will allow for installation of the SIRS recorder, transducers, and the oscillograph recording system on an RH-53D aircraft. Perform stress analysis as required to verify safety of flight.

2.2.3 Flight Test Plan

Prepare a flight test plan for a 30-day flight test program which will insure that all flight conditions are flown and the recording system operation can be verified.

2.2.4 Fabrication

Fabricate, assemble, calibrate and test the oscillograph system. Fabricate one installation kit. Test the SIRS recorder together with oscillograph system.

2.2.5 Installation

Install both recording systems on an RH-53D aircraft. Proof kit the installation design for the SIRS recorder and modify the design as necessary for subsequent production. Debug and test the recording systems to verify proper on-board operation.

2.2.6 Flight Test

In accordance with the flight test plan and using Navy flight test pilots, conduct the flight test of the recording system. Make minor modifications to the hardware and software to perfect the system. Flight test duration will not exceed 30 days.

2.2.7 Removal

Remove the recording systems from the aircraft and restore the aircraft to its original configuration.

2.3 Operational Evaluation

To gather a meaningful data sample, validate the ability of the system to monitor RH-53D usage data, and validate the damage assessment of the system, a six-month operational evaluation will be conducted on five RH-53D helicopters at ______ ________________.

2.3.1 Design Modifications

Evaluate the data obtained from the flight test program to determine the required modifications to the software and hardware for the recorders. Correct the drawings for the installation kits and recorders.

2.3.2 Playback Software

Using the data from the flight test, modify and verify the data playback software.

2.3.3 Fabrication

Fabricate five installation kits and four SIRS recorders. Refurbish the recorder in the flight test program. Test the recorders and package them for shipment.

2.3.4 Installation

Install the recording systems on five RH-53 helicopters at ____________________. Verify that all systems are operational.

2.3.5 Maintenance

For a period of six months, visit each site once per month and retrieve the data from the recorders. Service the recorders during each visit as required.

2.3.6 Data Processing

Using the modified playback software, process the data each month and produce the summary tables.

2.3.7 Data Analysis and Final Report

Upon the completion of the six-month operational evaluation, assess the performance of the SIRS recording system with

2.3.7 Data Analysis and Final Report (continued)

respect to its capability in measuring fatigue damage, functionality of the system, data handling techniques, data accuracy, reporting techniques, and cost. Prepare a final report documenting the results and presenting recommendations and conclusions.

3.0 Schedule

The total technical effort to submittal of a preliminary final report will be completed in 16 months with four months to modify the systems, two months for flight test, and 10 months for the operational survey phase including fabrication, installation, data acquisition, processing, analysis and preparation of the preliminary final report.

4.0 Documentation

Monthly progress reports will be submitted by the 15th of each month following the month being reported. A final report will be submitted at the end of the 16th month with 60 days allowed for review, rework and final submittal.

PRELIMINARY MILESTONE FORECAST

P.R. NR.________________ FOR________________________________

TASK		MONTHS																	
PHASE	DESCRIPTION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	System Design & Fabrication																		
2	Prototype Flight Test																		
3	Operational Survey																		
4	Analysis & Final Report																		

LEGEND: △ SCHEDULED EVENT; TIME SPAN; ▲ EVENT COMPLETED; ○ MODIFIED FORECAST; ANTICIPATED / ACTUAL CONTRACT EXPENDITURES

APPENDIX B

COST ANALYSIS SUMMARY SHEETS

FIVE-YEAR COSTS FOR 100-AIRCRAFT FLEET

Components	Cost with SIRS	Cost without SIRS	Savings
Control Horn	819,598	536,752	(282,946)
Rotating Swashplate	2,189,395	2,996,077	806,682
Stationary Swashplate	545,527	1,300,126	754,599
Tail Rotor Hub	418,929	97,631	(321,298)
Tail Rotor Pitch Actuator Shaft	508,519	791,787	283,268
Main Rotor Pushrod	530,570	212,190	(318,380)
Total	4,958,938	5,934,563	922,025

TEN-YEAR COSTS FOR 100-AIRCRAFT FLEET

Components	Cost with SIRS	Cost without SIRS	Savings
Control Horn	1,116,964	863,456	(253,508)
Rotating Swashplate	3,245,711	4,832,586	1,586,875
Stationary Swashplate	603,562	2,091,912	1,488,350
Tail Rotor Hub	478,375	160,751	(317,624)
Tail Rotor Pitch Actuator Shaft	574,800	1,275,474	700,674
Main Rotor Pushrod	654,649	342,210	(312,439)
Total	6,674,061	9,566,389	2,892,328

FIVE-YEAR COSTS FOR 200-AIRCRAFT FLEET

Components	Cost with SIRS	Cost without SIRS	Savings
Control Horn	1,574,536	1,074,260	(500,276)
Rotating Swashplate	4,337,980	6,012,606	1,674,626
Stationary Swashplate	1,045,018	2,604,126	1,559,108
Tail Rotor Hub	779,274	200,803	(578,471)
Tail Rotor Pitch Actuator Shaft	955,643	1,586,786	631,143
Main Rotor Pushrod	996,248	426,108	(570,140)
Total	9,688,699	11,904,689	2,215,990

TEN-YEAR COSTS FOR 200-AIRCRAFT FLEET

Components	Cost with SIRS	Cost without SIRS	Savings
Control Horn	2,169,167	1,727,641	(441,526)
Rotating Swashplate	6,450,639	9,682,610	3,231,971
Stationary Swashplate	1,161,066	4,197,421	3,036,355
Tail Rotor Hub	928,168	323,674	(574,494)
Tail Rotor Pitch Actuator Shaft	1,088,208	2,553,679	1,465,471
Main Rotor Pushrod	1,244,638	685,167	(559,471)
Total	13,008,886	19,170,192	6,161,306

FIVE-YEAR COSTS FOR 400-AIRCRAFT FLEET

Components	Cost with SIRS	Cost without SIRS	Savings
Control Horn	3,083,857	2,149,263	(1,024,594)
Rotating Swashplate	8,611,746	12,050,687	3,438,941
Stationary Swashplate	2,025,230	5,224,742	3,199,512
Tail Rotor Hub	1,493,431	402,957	(1,090,474)
Tail Rotor Pitch Actuator Shaft	1,849,835	3,177,066	1,327,231
Main Rotor Pushrod	1,927,588	852,683	(1,074,905)
Total	18,991,687	23,857,398	4,865,711

TEN-YEAR COSTS FOR 400-AIRCRAFT FLEET

Components	Cost with SIRS	Cost without SIRS	Savings
Control Horn	4,273,148	3,456,056	(817,092)
Rotating Swashplate	12,837,097	19,390,512	6,553,415
Stationary Swashplate	2,262,172	8,482,244	6,220,072
Tail Rotor Hub	1,731,193	652,086	(1,079,125)
Tail Rotor Pitch Actuator Shaft	2,114,941	5,110,559	2,995,618
Main Rotor Pushrod	2,424,602	1,371,069	(1,053,533)
Total	25,645,649	38,462,526	12,816,877

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